Temporal and spatial temperature variability and change over Spain during 1850–2005

M. Brunet,[1,2] P. D. Jones,[2] J. Sigró,[1] O. Saladié,[1] E. Aguilar,[1] A. Moberg,[3] P. M. Della-Marta,[4,5,6] D. Lister,[2] A. Walther,[7] and D. López[1]

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[1] We analyze temporal and spatial patterns of temperature change over Spain during the period 1850–2005, using daily maximum (T_{max}), minimum (T_{min}), and mean (T_{mean}) temperatures from the 22 longest and most reliable Spanish records. Over mainland Spain, a significant (at 0.01 level) warming of 0.10°C/decade is found for the annual average of T_{mean}. Autumn and winter contributed slightly more than spring and summer to the annual warming over the 1850–2005 period. The overall warming is also associated with higher rates of change for T_{max} than T_{min} (0.11° versus 0.08°C/decade for 1850–2005). This asymmetric diurnal warming increased in the twentieth century (0.17° versus 0.09°C/decade during 1901–2005). Nevertheless, at many (few) individual stations, the difference between T_{max} and T_{min} is not statistically significant over 1850–2005 (1901–2005). Principal Component Analysis has been carried out to identify spatial modes of Spanish long-term temperature variability (1901–2005). Three principal spatial patterns are found, Northern Spain, Southeastern and Eastern Spain, and Southwestern Spain. All three patterns show similar significant warming trends. The overall warming has been more associated with reductions in cold extremes, as opposed to increases in warm extremes. Estimated trends in the number of moderately extreme cold days (T_{max} < 10th percentile) and moderately extreme cold nights (T_{min} < 10th percentile) show significant reductions of 0.74 and 0.54 days/decade, respectively, over 1850–2005. Moderately extreme warm days and nights (T_{max} and T_{min} > 90th percentile) increased significantly but at lower rates of 0.53 and 0.49 days/decade.

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1. Introduction

[2] Surface air temperatures are rising globally [*Jones and Moberg*, 2003], although the warming has not been uniform across the globe, neither spatially nor seasonally [see also *Jones et al.*, 1999]. Some areas have warmed at greater rates than others; while some regions show no evidence of change or have even cooled. Furthermore, winter and spring have warmed at higher rates than summer and autumn. For much of Europe, this has led to a reduced seasonal contrast [*Jones*, 2001]. In this regard, the documentation and assessment of temperature variability and change at smaller than global, hemispheric, and continental scales (i.e. regional) is a key issue. This will help improve our understanding of long-term temperature variability and change and its associated mechanisms of forcing at regional scales.

[3] Within the last 10 years, many studies, focused on Spanish temperature change on a monthly basis, have shown evidence of warming over the country by analyzing data from groups of stations [e.g., *Oñate and Pou*, 1996; *Esteban-Parra et al.*, 2003a] or by developing regional time series for peninsular Spain [*Brunet et al.*, 2001a, 2001b; *Brunet et al.*, 2002; *Rodríguez-Puebla et al.*, 2002; *Brunet et al.*, 2005; *Brunet et al.*, 2006] or for different subregions [*Esteban-Parra et al.*, 1995; *Abaurrea et al.*, 2001; *Brunet et al.*, 2001c, 2001d; *Galan et al.*, 2001; *Horcas et al.*, 2001; *Staudt*, 2004; *Staudt et al.*, 2005; *Morales et al.*, 2005]. Even though these studies have used different spatial and temporal scales or diverse analytical approaches for assessing data quality and homogeneity, consistent and coherent temporal patterns of warming have been highlighted mainly for the second half of the twentieth century.

[1]Climate Change Research Group, University Rovira i Virgili, Tarragona, Spain.
[2]Climatic Research Unit, University of East Anglia, Norwich, UK.
[3]Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden.
[4]Federal Office for Meteorology and Climatology MeteoSwiss, Zurich, Switzerland.
[5]University of Bern, Institute of Geography, Climatology and Meteorology Research Group, Berne, Switzerland.
[6]National Climate Center, Bureau of Meteorology, Melbourne, Australia.
[7]Earth Sciences Centre, Göteborg University, Gothenburg, Sweden.

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All the findings indicate that the most remarkable feature of the twentieth century Spanish temperature change has been an abrupt and strong warming recorded from the early 1970s onward. Furthermore, over the course of the twentieth century, Spanish warming has not occurred in a steady nor monotonic way, as different periods of change have been identified. The warming has not been equally spread throughout the year, winter recording the greatest rates of change. Finally, the results of the majority of the studies on long-term (twentieth century) Spanish temperature change show that maximum temperature has increased at greater rates than minimum temperature both over the whole mainland Spain [*Brunet et al.*, 2001b; *Brunet et al.*, 2005; *Brunet et al.*, 2006] and over different Spanish subregions: the Middle Ebro River Basin [*Abaurrea et al.*, 2001], Northeastern Spain [*Brunet et al.*, 2001d], the southern Spanish plateau [*Galan et al.*, 2001], the Segura River Basin [*Horcas et al.*, 2001], and the northern Spanish plateau [*Morales et al.*, 2005]. However, different results (i.e., higher rates of change calculated for T_{min} than for T_{max}) were found by *Esteban-Parra et al.* [2003a], *Staudt* [2004], and *Staudt et al.* [2005] over mainland Spain and *Esteban-Parra et al.* [1995] over the northern Spanish plateau.

[4] A number of studies have focused on linking large-scale atmospheric circulation patterns to surface temperature variability over Europe and the Mediterranean Basin. *Maheras et al.* [1999], for example, have partially documented modes of variability over Spain on an annual and seasonal basis by establishing relationships between mean monthly temperatures for anomalously warm and cold months and large-scale atmospheric circulation over the Mediterranean area during 1860–1990 using one record (Barcelona) for Spain. *Pozo-Vázquez et al.* [2001a], using the 5° × 5° lat/long gridded data from the Climatic Research Unit (CRU) data set, have related European winter temperatures to the North Atlantic Oscillation (NAO) on a monthly scale during 1852–1997. Also, *Pozo-Vázquez et al.* [2001b] assessed the association between El Niño Southern Oscillation (ENSO) and the Northern Hemisphere (NH) sea level pressure and temperatures in Europe during winter, again using the 5° × 5° lat/long gridded data from CRU. Winter temperature variability over northern Spain and the associated atmospheric circulation (NAO, Arctic Oscillation, East-Atlantic) patterns and sea surface temperatures (SST) have been analyzed by *Sáenz et al.* [2001a, 2001b]. *Castro-Díez et al.* [2002] explored relationships between the NAO and the temperatures in southern Europe during the winter season. *Rodríguez-Puebla et al.* [2002] related Iberian Peninsula (IP) interannual temperature variability to large-scale atmospheric circulation patterns during 1949–2000 using raw data from 55 IP stations and air pressure fields. *Esteban-Parra et al.* [2003a, 2003b] analyzed Spanish spatial and temporal modes of temperature variability for 1880–1995 by studying annual and seasonal averages of daily maximum, minimum, and mean temperatures for 40 Spanish stations and established relationships between annual and seasonal temperatures and the NAO Index. *Xoplaki et al.* [2003] have assessed interannual and decadal variability of summer temperatures over the Mediterranean region and related these to large-scale atmospheric circulation and SST during the second half of the twentieth century. Their study included 10 Spanish temperature stations from the Global Historical Climatology Network (GHCNv2b) data set. *Sigró* [2004] and *Sigró et al.* [2005] explored relationships between interannual, intraannual, and summer [*Sigró et al.*, 2006] temperature change over Catalonia and atmospheric and Western Mediterranean SST modes of variability for the second half of the twentieth century.

[5] Previous analyses assessing changes in the extreme state of the climate have employed daily records for describing and analyzing trends of extreme temperatures over Europe, including some information for the Spanish subregion. *Moberg et al.* [2000] extensively analyzed day-to-day temperature variability over Europe for the 160- to 275-year-long European records in the framework of the EU-project Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources (IMPROVE). This project used the long-term Spanish daily temperature record of Cadiz. Another temperature record of daily maximum and minimum temperature, Barcelona/Fabra station, was analyzed by *Serra et al.* [2001] for the period 1917–1998. For the second half of the twentieth century and for a small part of the country, *Easterling et al.* [2003] and *Mokssit* [2003] documented trends in extreme temperatures over the southernmost part of Spain (6 stations) as part of a study aimed at developing extreme climate indices for Africa. Under the framework of the project European Climate Assessment & Dataset project (ECA&D), five daily Spanish temperature records were assessed when looking for changes in the extreme behavior of climate [*Klein Tank et al.*, 2002a, 2002b; *Klein Tank and Können*, 2003]. Occurrences of cold and warm extreme events and their relationships with large-scale atmospheric patterns have been examined for Madrid by *Prieto et al.* [2002] and *García-Herrera et al.* [2002]. *Prieto et al.* [2004] explored extremely cold days (T_{min} < 5th percentile) and their related synoptic conditions, local factors, and NAO influence on the annual occurrences of these events over mainland Spain from November to March for the period 1955–1998. This study focused the analysis on their associated health impacts. *Rodríguez-Puebla et al.* [2004] studied changes in summer maximum extreme temperatures (T_{max} > 90th percentile) over the IP for the second half of the twentieth century by employing 29 daily maximum temperature records obtained from the ECA&D data set and from the Spanish and Portuguese Meteorological Services. *Miró et al.* [2006] have explored daily summer temperatures (July and August) over the Valencia Region (eastern Spain) for 1958–2003 in order to analyze their evolution and tendency toward exhibiting a higher frequency of warmer days. Very recently, *Moberg et al.* [2006] examined daily temperature and precipitation extreme changes in Europe for the period 1901–2000, and *Della-Marta et al.* [2006] explored changes in summer heat-wave occurrence over western Europe for the period 1880–2003, relating them to large-scale forcings. Della-Marta et al. (The length of western European summer heat waves has doubled since 1880, submitted to *Journal of Geophysical Research-Atmospheres*, 2006, hereinafter referred to as Della-Marta et al., submitted manuscript, 2006) used a homogenized subset of the series from Europe, described in *Della-Marta et al.* [2006] and *Moberg et al.* [2006], for changes in the

daily maximum temperature probability density function (PDF) and the frequency of summer temperature extremes and heat waves. All three studies employed some of the Spanish daily adjusted records developed by *Brunet et al.* [2006] (henceforth *B*06) under the framework of the European Community (EC)-funded project European and North Atlantic Daily to Multidecadal Climate Variability (EMULATE) http://www.cru.uea.ac.uk/cru/projects/emulate).

[6] Many of these studies have focused on analyzing either shorter time series, fewer time series, or only one season of the year. There is, then, a need to further investigate the changes in the mean and extreme state of the Spanish thermal climate. An assessment of spatial and temporal modes of temperature variability, in order to provide a more complete picture on temperature variability and change across the year, is still lacking. In this regard, a comprehensive analysis covering most of the instrumental period will allow improved understanding of regional changes that may be related to human-induced warming [e.g., *Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. The absence of sufficiently reliable daily climate records has hampered our attempts to study the long-term temporal and spatial variability in extreme temperatures. This justifies undertaking a more complete assessment of the temporal change in both the mean and extreme state of the Spanish thermal climate.

[7] With this background in mind, a new daily adjusted data set composed of the longest 22 Spanish daily temperature records (maximum, minimum, and mean temperatures) has been developed within the framework of the EC-funded project EMULATE [*B*06]. In this context and given the hitherto limited spatial coverage of available daily time series over Spain, one of the initial aims for the present authors was to locate, recover, digitize, quality control, and homogenize the longest and most reliable Spanish daily temperature and precipitation records in order to develop a comprehensive analysis of long-term change in the mean and extreme state of Spanish climate. This contributes to the overall EMULATE objectives for the whole of Europe.

[8] An assessment of long-term temperature variations and trends has been conducted by creating the Spanish Temperature Series (STS), composed of the regional T_{mean}, T_{max}, and T_{min} time series developed from the 22 daily adjusted Spanish records, which cover for the very first time the bulk of the Spanish instrumental era with a reasonably spatially resolved coverage. Temporal changes of STS are analyzed on an annual and seasonal basis in order to explore both changes in daily mean and daily extreme temperatures and assess the contribution of the later variables to the asymmetrical diurnal warming documented at larger spatial scales (global scale by i.e., *Easterling et al.* [1997]). A second aspect assessed in this paper is the spatial patterns of long-term Spanish temperature variability. We document the spatial response to long-term T_{mean} changes within the different Spanish subregions. Finally, an analysis of long-term changes in temperature extremes has been carried out to address what parts of the daily temperature distribution can better explain the observed Spanish warming.

[9] The paper is organized as follows: the Spanish temperature network, the reassessment of the "screen bias" minimization applied to the monthly T_{max} and T_{min} raw data, and the development of the STS are described and discussed in section 2 together with the analytical techniques employed in this study. Section 3 examines the time variations and trends of the STS during 1850–2005 and discusses the different rates of warming estimated for daily extreme temperatures (T_{max} and T_{min}). Section 4 is devoted to an analysis of the spatial patterns of T_{mean} change over Spain for the shorter period 1901–2005, suggesting some areas where further work might be useful. Changes in the occurrence of extreme temperatures are analyzed in section 5, which also considers which parts of the temperature distribution might explain more of the warming observed in the Spanish series. Finally, in section 6, we summarize and discuss some of the results.

2. The Creation of the STS and Description of Analysis Techniques

2.1. Data Details and the New Approach to Minimizing the "Screen Bias" in the STS

[10] The selected temperature network, which incorporates the 22 longest and most reliable daily Spanish records and which extends back to the midnineteenth century, is shown in Tables I, II and III of the study of *B*06 and displayed here in Figure 1. Figure 1 shows approximate geographical locations, length of records, and elevations. The tables also provide similar information plus the data sources. Table VIII of *B*06 also provides dates of Stevenson screen introduction in the Spanish meteorological network. Although the bulk of these data have been obtained in digital and hard-copy form from the Instituto Nacional de Meteorología (INM, Spanish Meteorological Office), a number of other sources of meteorological information have been used in this study, particularly for the nineteenth century (Table III in *B*06). This network covers the entire country reasonably well, encompassing the main Spanish climate types (Oceanic and Mediterranean) and subtypes (Atlantic, 2; Continental, 10; Eastern Mediterranean coast, 2; Southern, 6; and Southeastern, 2 stations) according to *Martin-Vide and Olcina*'s [2001] Spanish climate classification.

[11] As fully documented in the companion paper [*B*06], raw daily maximum (T_{max}) and minimum (T_{min}) temperatures have been subjected to different quality control (QC) tests in order to identify and flag major errors of digitization as well as to ensure internal consistency and temporal and spatial coherence of the data. Gross error checks (aberrant values, problems with the decimal point, calendar dates, etc.), $T_{\mathrm{max}} < T_{\mathrm{min}}$ values, consecutive values repeating at least four times, temperature values greater than ±4 standard deviation threshold for the candidate record and its group of reference stations, and values exceeding the expected amount of change between consecutive observations have been exhaustively assessed in the raw data. More detailed information on both the applied QC and the results are shown and discussed in *B*06.

[12] Another major issue for undertaking any homogeneity assessment is that before the generalized use of the Stevenson shelter, different types of open stands were employed to protect thermometers. The temporal changes in thermometer screens around the world have been documented by *Parker* [1994]. According to this study, temperature readings taken using pre-Stevenson screens are likely to be biased to a higher or lower degree depending on

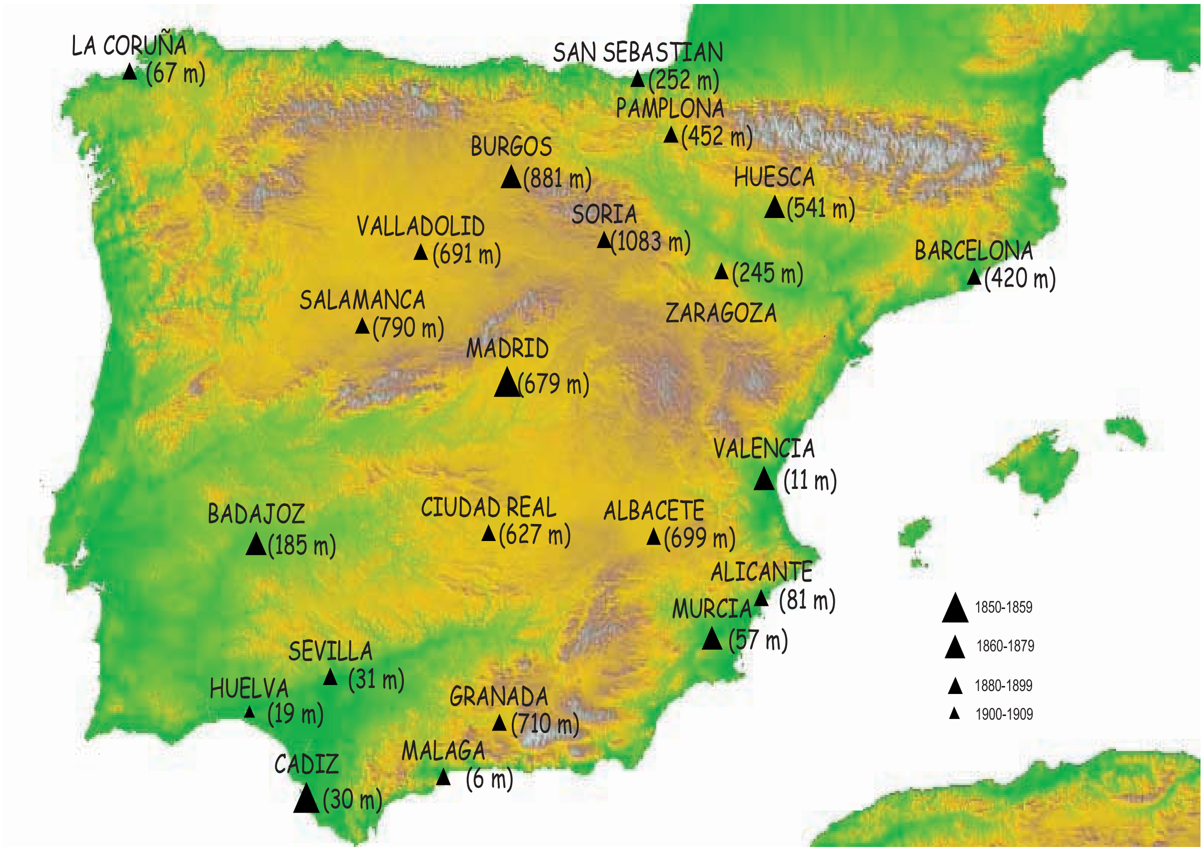

Figure 1. Location map of the 22 Spanish stations used to develop the Spanish Daily Adjusted Temperature Series (SDATS). Names, elevations, and approximate lengths of record are shown.

latitude and observation time during the day and year and hence will likely have a diverse impact on daily extreme (maximum or minimum) temperature. For the Mediterranean climate, *Nicholls et al.* [1996] have shown that presheltered temperatures in Australia are likely to bias the longest temperature records, tending to mainly overestimate $T_{\max}$ and very slightly underestimate $T_{\min}$ values compared with the modern-screen period. Similar screen bias has also been documented over Spain by *Brunet et al.* [2004]. This bias constitutes one of the potential causes, among others, of homogeneity breaks in the earliest parts of the longest Spanish temperature records. At the same time, it is a difficult bias to account for when employing a relative homogeneity assessment for testing and adjusting long records, as it was a contemporary and a common feature of the early surface observational network. For this reason, dual air temperature observations were and are being carried out in the framework of the SCREEN project at the meteorological gardens of La Coruña and Murcia ("Assessment and minimization of screen bias incorporated into the longest Spanish air temperature records by time, changing thermometric exposures throughout dual temperature observation (SCREEN)" http://wwwa.urv.net/centres/Departaments/geografia/clima/currentresearch.htm). These locations were chosen as being representative of the most contrasting IP climate variants, the Atlantic climate type and the Mediterranean semiarid climate subtype. In this project, the nineteenth century Montsouris stand (the French stand) was built and operated according to details given in publications from the period [e.g., *Rico Sinobas*, 1857; *Instituto Central Meteorológico* (*ICM*), 1893; *Angot*, 1903].

[13] A preliminary empirical minimization of the screen bias, before undertaking the homogeneity testing of the records, was carried out when adjusting the raw monthly averages of 20 out of the 22 Spanish daily $T_{\max}$ records in the quoted companion paper [*B*06], as only 1 year of paired observations were then available. The assessment approach of *B*06 consisted of subtracting from the $T_{\max}$ monthly raw values the median of the daily differences estimated from simultaneous $T_{\max}$ readings recorded under both the old (our reconstructed Montsouris stand) and new (Stevenson screen) exposures. After collecting two complete years of simultaneous daily temperature observations (from July 2003 to June 2005 in La Coruña and from March 2003 to February 2005 in Murcia), we have reassessed both the scheme employed for minimizing the screen bias from the longest Spanish records and its application to also adjust this bias in the longest $T_{\min}$ records.

[14] Here we describe the new procedure followed for a more robust minimization of screen bias from 21 out of the 22 Spanish monthly $T_{\max}$ and $T_{\min}$ raw averages before subjecting these time series to the relative homogeneity assessment process. The records for Malaga have not been adjusted, as our metadata for this station indicated that the thermometers were exposed for an undefined period between the last decades of the nineteenth century and early twentieth century inside a louvred rectangular hut of 2 m × 3 m × 2 m with a door opening to the north. We also

Table 1. Spearman (Rho) Correlation Matrix Between Daily Maximum and Minimum Temperatures Recorded With a Montsouris Stand and a Stevenson Screen at the Meteorological Garden of Murcia, the "Screen Bias" for Maximum (ΔT_{max}) and Minimum (ΔT_{min}) and Other Related Daily and Subdaily Meteorological Variables (see Text for Details)[a]

	T_{max} Stevenson	T_{max} Montsouris	ΔT_{max}	T_{min} Stevenson	T_{min} Montsouris	ΔT_{min}
Cloud Amount 07	**−0.39**	**−0.39**	**0.18**	**−0.11**	**−0.11**	0.01
Cloud Amount 13	**−0.43**	**−0.42**	*0.09*	**−0.16**	**−0.16**	0.06
Cloud Amount 18	**−0.35**	**−0.35**	*0.09*	**−0.15**	**−0.15**	0.01
Daily Average Wind Speed	**0.23**	**0.23**	**−0.14**	**0.27**	**0.26**	0.02
Daily Sunshine	**0.66**	**0.67**	**−0.37**	**0.39**	**0.39**	*−0.09*
Air Pressure 00	**−0.11**	**−0.11**	0.05	**−0.21**	**−0.21**	**−0.11**
Air Pressure 07	**−0.11**	**−0.11**	0.05	**−0.20**	**−0.20**	**−0.10**
Air Pressure 13	**−0.15**	**−0.16**	0.08	**−0.20**	**−0.20**	*−0.10*
Air Pressure 18	**−0.21**	**−0.21**	**0.11**	**−0.24**	**−0.24**	−0.08
ΔT_{max}	**−0.52**	**−0.56**	**1**	**−0.48**	**−0.48**	0.07
ΔT_{min}	*−0.09*	*−0.09*	0.07	**−0.19**	**−0.21**	**1**
T_{max} Montsouris	**0.99**	**1**	**−0.56**	**0.87**	**0.86**	*−0.09*
T_{max} Stevenson	**1**	**0.99**	**−0.52**	**0.86**	**0.86**	*−0.09*
T_{min} Montsouris	**0.86**	**0.86**	**−0.48**	**0.99**	**1**	**−0.21**
T_{min} Stevenson	**0.86**	**0.87**	**−0.48**	**1**	**0.99**	**−0.19**

[a]Bold (italic) indicates significance at 1% (5%) confidence level.

discuss the impact of this new approach compared to that previously described in *B*06. From the 2 years of simultaneous daily temperature and other related meteorological variables (i.e., daily values of sunshine, cloud coverage, air pressure, and wind speed and also subdaily observations) recorded at both locations, we first correlated these variables in order to explore the most robust relationships among them. Tables 1 and 2 show results for Murcia and La Coruña, respectively, both indicating that, as expected, the highest Spearman (Rho) correlation coefficients have been estimated between T_{max} and T_{min} series recorded under Montsouris stands and Stevenson screens ($r > 0.99$). Also, the highest correlations have been found between the screen bias of maximum temperature (ΔT_{max}) and T_{max} temperatures recorded under Montsouris screens at both locations (Tables 1 and 2). Series of ΔT_{max} have been estimated as the difference between daily readings registered under both exposures (Montsouris minus Stevenson). These correlations show an inverse relationship between both measurements indicative of higher maximum temperatures leading to a higher screen bias. Other significant relationships, but with much lower correlation strength, have been found between ΔT_{max} and sunshine and wind speed (sunshine, wind speed, and cloud cover) for Murcia (La Coruña). The relationships between ΔT_{min} and the other variables at both locations show much weaker correlation coefficients both between the T_{min} series recorded under Montsouris stand and the other related variables.

[15] On the basis of the highest correlation coefficients and the linear relationship established between temperature observations taken under both exposures, we have developed two linear regression models, one for each location, using Montsouris T_{max} readings to predict Stevenson T_{max} values. Both models explain the 99% of T_{max} series variance for Murcia and the 98.6% for La Coruña, and their expressions are

$$\mathrm{Tc} = -0.508 + (0.975\ \mathrm{Tr})\ \text{for Murcia and}$$
$$\mathrm{Tc} = 0.059 + (0.949\ \mathrm{Tr})\ \text{for La Coruña}$$

Where Tr is the raw data measured under Montsouris stands and Tc the corrected temperature as measured under Stevenson screens. The Spanish stations corrected with the Murcia and La Coruña equations are listed in Table VIII of the companion paper [*B*06]. This time we have applied this scheme also to minimize Cadiz T_{max} record for 1850–1875, as new recovered metadata showed that at this station, thermometric observations were also taken under

Table 2. Same as Table 1 but for Observations Taken at the Meteorological Garden of La Coruña

	T_{max} Stevenson	T_{max} Montsouris	ΔT_{max}	T_{min} Stevenson	T_{min} Montsouris	ΔT_{min}
Cloud Amount 07	**−0.21**	**−0.21**	*0.09*	0.07	0.07	−0.02
Cloud Amount 13	**−0.25**	**−0.27**	**0.23**	−0.03	−0.03	0.03
Cloud Amount 18	**−0.22**	**−0.23**	**0.15**	−0.07	−0.07	0.01
Daily Average Wind Speed	**−0.34**	**−0.35**	**0.25**	**−0.21**	**−0.20**	**−0.19**
Daily Sunshine	**0.37**	**0.40**	**−0.35**	**0.13**	**0.13**	0.00
Air Pressure 00	−0.05	−0.06	**0.12**	**−0.11**	**−0.11**	−0.06
Air Pressure 07	−0.05	−0.06	0.07	**−0.11**	**−0.11**	−0.05
Air Pressure 13	−0.07	−0.07	0.02	**−0.11**	*−0.10*	−0.03
Air Pressure 18	*−0.08*	*−0.08*	0.00	*−0.10*	*−0.10*	−0.01
ΔT_{max}	**−0.26**	**−0.36**	**1**	**−0.19**	**−0.19**	**−0.14**
ΔT_{min}	**0.24**	**0.25**	**−0.14**	**0.25**	**0.22**	**1**
T_{max} Montsouris	**0.99**	**1**	**−0.36**	**0.87**	**0.87**	**0.25**
T_{max} Stevenson	**1**	**0.99**	**−0.26**	**0.88**	**0.88**	**0.24**
T_{min} Montsouris	**0.88**	**0.87**	**−0.19**	**0.99**	**1**	**0.22**
T_{min} Stevenson	**0.88**	**0.87**	**−0.19**	**1**	**0.99**	**0.25**

Table 3. Observed Versus Predicted Monthly Differences (ΔT_{max}) of Daily Maximum Temperatures (in °C) Recorded With the Stevenson and Montsouris Exposures at the Meteorological Gardens of La Coruña and Murcia for the 2 Years of Paired Temperature Observations (See Text for Details)

La Coruña					Murcia				
Years	Months	Montsouris T_{max} Averages	Observed ΔT_{max}	Predicted ΔT_{max}	Years	Months	Montsouris T_{max} Averages	Observed ΔT_{max}	Predicted ΔT_{max}
2003	7	22.99	−1.19	−1.17	2003	3	21.60	−1.01	−1.05
2003	8	26.32	−1.09	−1.37	2003	4	24.53	−1.11	−1.12
2003	9	23.97	−1.10	−1.23	2003	5	28.23	−1.23	−1.21
2003	10	18.47	−0.79	−0.91	2003	6	34.95	−1.39	−1.38
2003	11	17.03	−0.56	−0.83	2003	7	36.82	−1.33	−1.43
2003	12	14.48	−0.42	−0.68	2003	8	36.91	−1.21	−1.43
2004	1	14.96	−0.60	−0.71	2003	9	31.90	−1.22	−1.30
2004	2	15.51	−1.00	−0.74	2003	10	25.70	−0.99	−1.15
2004	3	15.53	−1.14	−0.74	2003	11	21.17	−0.77	−1.04
2004	4	16.35	−1.06	−0.79	2003	12	18.52	−0.87	−0.97
2004	5	19.59	−1.32	−0.98	2004	1	20.68	−0.76	−1.02
2004	6	23.54	−1.50	−1.21	2004	2	19.15	−1.02	−0.99
2004	7	23.41	−1.43	−1.20	2004	3	20.49	−1.16	−1.02
2004	8	24.13	−1.25	−1.24	2004	4	22.96	−1.35	−1.08
2004	9	23.32	−1.08	−1.19	2004	5	25.82	−1.59	−1.15
2004	10	19.04	−0.68	−0.95	2004	6	33.80	−1.51	−1.35
2004	11	15.87	−0.39	−0.76	2004	7	34.63	−1.59	−1.37
2004	12	14.13	−0.36	−0.66	2004	8	36.29	−1.42	−1.41
2005	1	14.28	−0.57	−0.67	2004	9	32.49	−1.34	−1.32
2005	2	12.50	−0.76	−0.57	2004	10	28.75	−1.20	−1.23
2005	3	17.38	−0.79	−0.85	2004	11	21.17	−0.94	−1.04
2005	4	17.41	−1.11	−0.85	2004	12	17.63	−0.90	−0.95
2005	5	19.59	−1.26	−0.98	2005	1	17.62	−0.96	−0.95
2005	6	23.29	−1.12	−1.19	2005	2	16.91	−1.12	−0.93

an open stand during the earliest pre-1875 instrumental period [*González*, 1992].

[16] It could be argued that the transfer of both linear expressions to the other 19 thermometric records is not correct because of differences in location details (i.e., in elevation or proximity to the sea) between sites. Strictly and climatologically speaking, both expressions are only valid for adjusting the early Murcia and La Coruña temperature data, but there are several lines of reasoning for transferring these linear models to conservatively minimize this untreatable bias from the other affected records. First, this early bias was a common feature for the entire network affecting all the thermometric records, as documented in our metadata. This made their correction difficult, particularly when employing a relative homogeneity assessment. So other absolute approaches are necessary for dealing with it. Second, when pre-Stevenson exposures were changed to the new ones, no parallel measurements between the old and new screens were made (except in a few cases, e.g., Adelaide [*Nicholls et al.*, 1996] or in Madrid for the Mediterranean climate, at least to the authors' knowledge). Third, geographical factors of the Iberian Peninsula cause differences in annual temperature cycles between locations (higher annual temperature range for inland Spain and lower in coastal areas); the annual cycles are more similar than might be intuitively expected. Fourth, because of the lack of contemporary parallel temperature observations, the authors cannot estimate site-specific linear regression models for each station because of economic considerations. Fifth, we have fortunately recovered paired temperature observations made at Madrid from March to December 1893, when the new Stevenson screen was introduced and operated in parallel with the older stand. An analysis of these data (just 10 months of paired daily observations) has been performed, showing similar signs of the bias for both temperature variables (T_{max} and T_{min}) but with a slightly larger impact on T_{max} than that observed in our own comparisons at Murcia or La Coruña. These Madrid observations give the authors faith in the reality of the bias adjustments at stations located in inland Spain with higher elevations and far away from the two experimental coastal locations. Finally, the application of both linear equations is dependent upon the actual T_{max} monthly value to be corrected with the different amplitudes of the annual temperature cycle at each station being considered when subtracting the bias from the old monthly averages. The authors believe that transferring the Murcia and La Coruña regression equations to the other climatically related stations minimizes the bias, although it is unlikely to completely reduce it.

[17] To test the performance of both linear regression models, we have compared the observed monthly differences between readings taken under Stevenson and Montsouris exposures with the predicted values. Table 3 shows the monthly averages of daily maximum temperatures recorded under Montsouris stands at both locations, the observed monthly differences (Stevenson minus Montsouris), and the predicted differences for the 2 years of paired observations. As can be deduced from Table 3, the performance of both linear regression models predicting T_{max} monthly differences between both exposures is highly accurate, with an average difference between the observed and predicted monthly average of 0.1°C for Murcia and 0.2°C for La Coruña.

[18] For minimum temperature, linear regression models do not provide good adjustments because of the weak relationships established between the T_{min} values recorded under Montsouris stands and the screen bias estimated from T_{min} series (ΔT_{min}), as well as the very weak and constant

Table 4. Monthly Adjustments (in °C, With the 95% Confidence Interval in Brackets) Estimated From Difference Time Series of Daily Minimum Temperature Recorded With the Montsouris and Stevenson Exposures at the Two Spanish Meteorological Gardens of La Coruña (Northwestern Spain) and Murcia (Southeastern Spain) Where the Paired Observations Were Simultaneously Recorded for Minimizing "Screen Bias" of the Pre-Stevenson Records (See Text for Further Details)

Months	La Coruña	Murcia
Jan	0.18 (0.14/0.22)	0.27 (0.21/0.33)
Feb	0.16 (0.10/0.21)	0.19 (0.14/0.24)
Mar	0.17 (0.13/0.21)	0.13 (0.08/0.18)
Apr	0.14 (0.09/0.19)	0.16 (0.10/0.22)
May	0.14 (0.10/0.17)	0.16 (0.10/0.22)
Jun	0.21 (0.17/0.24)	0.21 (0.16/0.26)
Jul	0.17 (0.14/0.20)	0.13 (0.09/0.17)
Aug	0.26 (0.22/0.30)	0.19 (0.14/0.24)
Sep	0.24 (0.20/0.29)	0.11 (0.06/0.17)
Oct	0.20 (0.16/0.23)	0.27 (0.22/0.32)
Nov	0.19 (0.11/0.27)	0.21 (0.15/0.26)
Dec	0.19 (0.12/0.26)	0.28 (0.23/0.33)

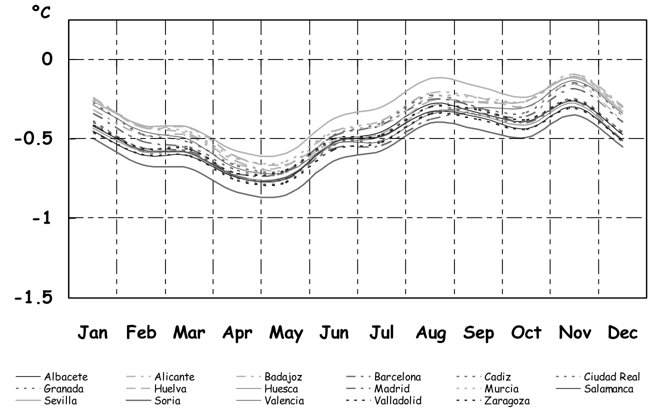

Figure 3. Monthly differences between the old adjustments in *B*06 (see Table VII of that paper) and the new approach applied to the 21 Spanish raw monthly maximum temperatures in order to minimize the "screen bias" from these records by employing the equations estimated from Murcia data (see text for details).

magnitude of the screen bias across the year, as shown in Table 4. This table provides the monthly median differences estimated during the 2 years of dual daily minimum temperature observations recorded under both exposures and locations together with their 95% confidence intervals. Given these statistically significant differences, we have also opted for minimizing the screen effects from the minimum temperature series by adding the estimated monthly medians to the monthly $T_{\min}$ raw averages of the 21 Spanish records. The application of Murcia and La Coruña adjustments to the $T_{\min}$ monthly raw averages of the 21 Spanish records is made according to the same association as for $T_{\max}$ as in Table VIII of the companion paper [*B*06]. The Cadiz $T_{\min}$ record is now corrected with Murcia monthly factors during 1850–1875.

[19] Finally, we discuss the impact of the new procedure undertaken for screen bias minimization from the longest 21 Spanish monthly maximum temperature records compared to that previously followed in *B*06. Figure 2 shows annual averaged differences between the application of the old and new schemes, and Figures 3 and 4 show monthly differences between the factors estimated with the old procedure minus that resulting from the new approach (that is, negative differences indicate reductions in the magnitude of the correction with respect to the old approach) and calculated from the 2 years of paired observations and for the 21 $T_{\max}$ records. For comparison purposes, see the former factors shown in Table VII of the companion paper. Figure 3 shows those stations adjusted with the Murcia linear equation, and Figure 4 shows those corrected with the La Coruña equation. The application of the new "screen" factors to the annual $T_{\max}$ raw data, which have been subtracted from the original series, has mainly reduced the magnitude of the earlier adjustments by about 0.25°C on average during the 1864–1916 period; meanwhile for the 1850–1853 (1854–1862) periods, the new scheme has increased the adjustments by about 0.45°C (0.13°C) in the earliest parts of the records as the Cadiz data have also this time been subjected to the screen minimization procedure. On a monthly scale and for the records corrected with the Murcia linear equation, the largest difference between both approaches is found from March to June with a reduction with respect to the former correction that ranges from 0.85°C for Soria to 0.60°C for Seville in April and

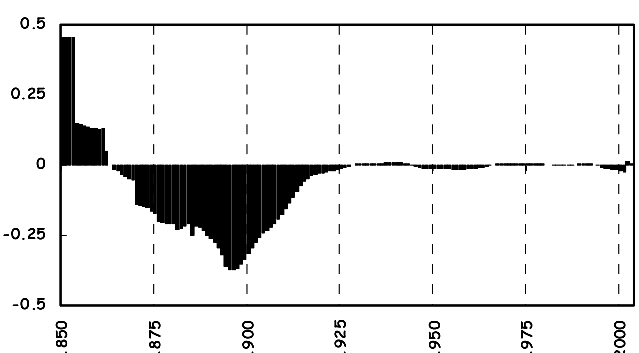

Figure 2. Annually averaged differences between the old adjustments in *B*06 and the new factors applied to the 21 Spanish raw monthly temperature records (old minus new approach) in order to minimize the "screen bias" from these records.

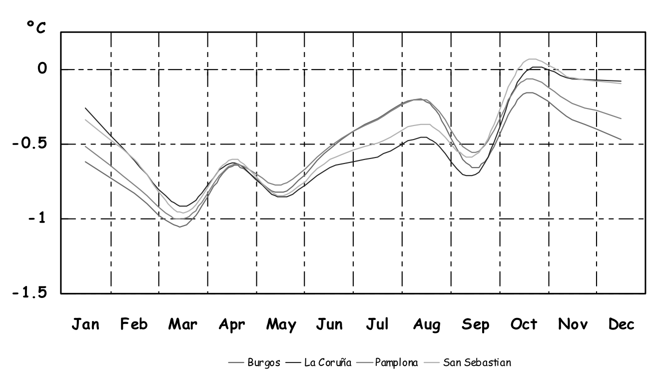

Figure 4. Same as Figure 3 but for records adjusted with the linear regression defined with La Coruña data.

May (Figure 3); meanwhile, the differences from July to February show lower reductions especially for November. The monthly differences estimated using the La Coruña linear regression model show a similar intraannual pattern: maximum reductions from February to June (March with the largest differences) and the minimum from July to January, except September, with October being the month less altered by the new approach (Figure 4).

[20] A relative homogeneity reassessment of monthly averaged data, based on the Standard Normal Homogeneity Test (SNHT) developed by *Alexandersson and Moberg* [1997], has then been applied to the previously adjusted (for screen bias) and updated to 2005 records. To interpolate monthly correction factors to a daily basis, a scheme similar to that used by *Vincent et al.* [2002] has been followed. Complete details on the procedures followed, to adjust maximum and minimum daily data, are provided in the companion paper [*B*06].

[21] As described in *B*06, the authors have paid particular care to avoid, as far as possible, and to minimize artificial trends related to, i.e., spurious urban influences in the records. The authors followed a double strategy to avoid potentially biased records related to "urban heat island" (UHI) effects. First, we developed, where possible, records using data from small- to medium-sized cities during the nineteenth century and the first half part of the twentieth century and used observations taken from the mid-twentieth century onward from the nearest nonurban stations situated mainly at airfields and airports. Second, for those records that could not be composed with time series taken in nearby rural or nonurban locations because of the absence or low quality and continuity of the data in these nearby monitoring sites, the authors opted to minimize any artificial trend present in the data, especially those related to UHI effects, by detecting and adjusting the series using the statistics and factors involved in the application of the homogeneity tests chosen. The authors are confident that the Spanish Daily Adjusted Temperature Series (SDATS) series are reasonably free of spurious urban warming trends.

[22] Here in Figure 5, we show the annual variations of the 22 Spanish daily adjusted and updated maximum and minimum temperature records. To compare both the impact of the new screen minimization applied to the data with respect to the former and the rehomogenization procedure described in *B*06, this figure should be compared with Figures 9 and 10 (bottom) in *B*06. The main effect on both the 22 $T_{\max}$ and $T_{\min}$ time series has been to "warm" the data for the prescreen period. This new daily adjusted data set, the SDATS, is composed of the 22 adjusted long records of daily maximum and minimum temperatures and derived daily mean temperature (T_{mean}).

2.2. Methods of Analysis

[23] Regional time series of daily mean, maximum, and minimum temperatures for the period 1850–2005, the STS, have been constructed by averaging daily anomalies and then adding back the base-period mean, according to the method of *Jones and Hulme* [1996] of separating temperature into its two components (the climatology and the anomaly). In order to adjust the variance bias present in regional mean time series associated over time with varying sample size, we have adopted and applied here the approach

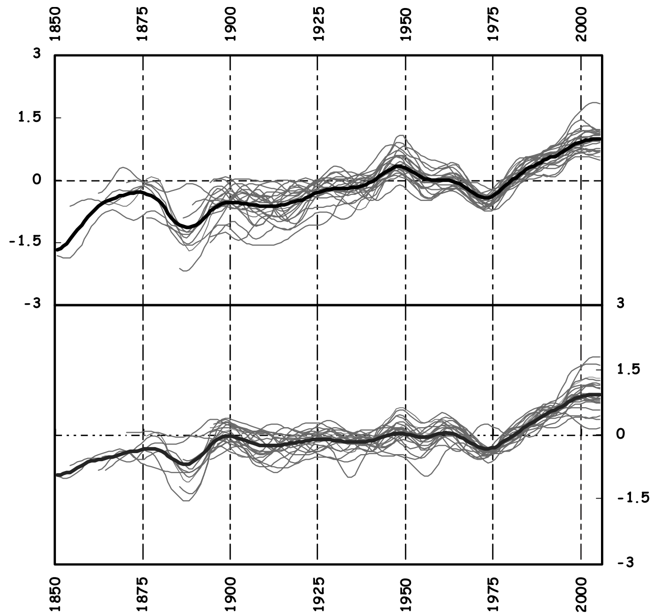

Figure 5. Annual variations (1850–2005) of the new 22 Spanish daily maximum (top) and minimum (bottom) adjusted temperature records (thin grey lines) and their corresponding mean (thick black line) expressed as anomalies from 1961 to 1990 and smoothed with a 13-year Gaussian filter.

developed by *Osborn et al.* [1997] to correct this bias in STS, according to the following expression:

$$Y(t) = X(t)\sqrt{\frac{n'(t)}{n'(n=N)}},$$

where $Y(t)$ is a time series with a variance independent of sample size, $X(t)$ is the original regional mean time series, N is the maximum sample size (22 in this case), and n' is the effective independent sample size:

$$n' = \frac{n(t)}{1+(n(t)-1)\bar{r}},$$

where n is the number of records and $\bar{r}$ is the mean correlation between all pairs of time series. Temporal variations on an annual and a seasonal basis have been assessed by means of a Gaussian low-pass filter of 13 terms in order to suppress high-frequency fluctuations on timescales less than decadal. The Gaussian filter approximates a decadal smoother with sigma equal to 3 standard deviations. It has six weights either side of a central weight (so 13 in all). To extend the smoothed series to the starts/ends of the series, additional values (equal to the average of the last/first 6 years) are added. Temperature change, explained by a linear trend fit over the entire period and several subperiods of rising and falling temperatures, has been calculated on an annual and a seasonal basis by adapting *Sen*'s [1968] estimator of the slope. Our application of this method is similar to that undertaken by *Zhang et al.* [2000] in a study of annual temperature and precipitation change over Canada and in extreme wave heights over Northern Hemisphere oceans [*Wang and Swail*, 2001]. All trends are tested for statistical significance at the 0.01 level unless otherwise stated. The 95% confidence intervals of trend coefficients have also been estimated from tabulated values [*Kendall*, 1955] and are provided in the text.

[24] To extract the dominant spatial modes of variability in SDATS, the 22 adjusted mean temperature records were converted to standardized anomalies with respect to the 1961–1990 base period [by dividing them by their standard deviations (SD)] before using a Principal Component Analysis (PCA) in *S* mode with the correlation matrix on a monthly timescale. We retained those principal components (PCs) exceeding the 0.7 threshold of Kaiser's rule [*Kaiser*, 1958] as well as inspection of the scree plots for summarizing the interannual variability of daily mean temperature data during the period 1901–2005 when data completeness is at its best. The resulting principal components (PCs) have been subjected to Varimax rotation in order to avoid domain dependence possibly imposed on unrotated components [*Richman*, 1986]. Maps of the Rotated Principal Components Analysis (RPCA) loading factors and the associated score series have been produced. For each spatial pattern, a subregional time series has been calculated by averaging daily anomalies and then adding back the base-period mean of those individual time series comprising each pattern with a loading $\geq$0.60, as made by *Brunetti et al.* [2006] on their analysis on long-term temperature and precipitation change over Italy. For comparison purposes among the spatial patterns, robust linear trends for each spatial pattern have been calculated for different subperiods, and the 95% confidence intervals of the trends have also been estimated. Finally, anomalous warmer and cooler episodes and other interannual variations have also been studied.

[25] An assessment of the long-term change in extreme temperatures was undertaken to identify important changes in the probability density function of the Spanish temperature records. This was performed using the RClimDex software package [*Zhang and Yang*, 2004] on an annual basis that uses a robust method of estimating trends, following the methods of estimation of *Zhang et al.* [2000] and *Wang and Swail* [2001]. Analysis on a seasonal basis has also been carried out by employing the EMULATE extreme indices software http://www.cru.uea.ac.uk/cru/projects/emulate/public/) developed by *Walther* [2004]. We assess trends in percentile-based temperature indices (daily 10th and 90th percentiles for $T_{\max}$ and $T_{\min}$), which describe the number of "moderately extreme cold" days and nights and "moderately extreme warm" days and nights, respectively, for the period 1850–2005. An RPCA has been performed on these time series as well in order to analyze spatial patterns of Spanish long-term change in extreme temperatures for the shorter period of 1901–2005 when data availability and continuity is almost complete.

3. Time Variations and Trends of Long-Term Spanish Temperature Change

[26] This section deals with both long-term behavior and decadal variability of the STS. In the first subsection, we show and discuss the long-term behavior of the STS, while in the second, we address the decadal variability of the STS.

3.1. Long-Term Change in the STS

[27] Figure 6 shows time variations of daily mean temperatures both on an annual and a seasonal basis. Table 5 gives the temperature change (°C) explained by a linear trend fit over the entire period and several subperiods of rising and falling temperatures. These subperiods have been determined by visually inspecting the annual Gaussian filter curve. Statistically significant warming is evident over the entire period and over the shorter subperiod of 1901–2005 both on an annual basis and for all the seasons. Seasonal contributions to annual warming are very similar, although rates of change for winter and autumn are slightly greater for 1850–2005 (Table 5). A somewhat contrasting seasonal contribution to the higher annual warming has been identified over the 1901–2005 period: winter and summer show the greatest contribution, followed by the equinoctial seasons.

[28] The highest and lowest monthly, seasonal, and annual temperature anomaly values in the STS T_{mean} for the period 1850–2005 are listed in Table 6. Eleven out of the 17 warmest values have been recorded since 1989, with 2003 the warmest year and summer in the Spanish instrumental record. Twelve out of the 17 lowest values are spread across the 1850–1950 period. The most recent coldest value on a seasonal basis was summer 1977 and April 1986 on a monthly basis. February 1956 is the coldest anomalous month of the entire record. Ranking the 10 warmest and 10 coldest monthly, seasonal, and annual temperature anomaly averages (not shown) of the 170 (12 months + 4 seasons + annual $\times$ 10) warmest values shows that 82 have occurred since 1989. Moreover, all 10 of the 10 warmest annual anomaly values have occurred since 1989. Summer is the season that presents the highest occurrence of warmest values for this last period (8 out of 10), followed by winter and spring (6 out of 10 for each season).

[29] In order to explore which daily extreme temperature ($T_{\max}$ or $T_{\min}$) has made the greatest contribution to the warming of the T_{mean} regional series, we assess here both long-term variations and trends of daily maximum and minimum regional series. Figure 7 shows seasonal and annual variations of daily maximum (left panel) and minimum (right panel) STS, and Table 5 provides the corresponding linear trend fit over the entire period and the other identified subperiods of rising and falling temperatures. Statistically significant trends have been calculated over the longest periods of 1850–2005 (1901–2005) for both variables, and these indicate that Spanish warming is mainly associated with the moderately (strongly) higher rates of change estimated for $T_{\max}$ series than for $T_{\min}$ series. These indicate that daytime temperatures have tended to increase faster than nighttime temperatures over the period 1850–2005 and particularly over the 1901–2005 period, although in some cases, this difference is not statistically significant. It is clear over mainland Spain that a larger increase in $T_{\min}$ compared to $T_{\max}$ has not occurred. This differential diurnal warming at the annual scale has mainly been contributed to by the equinoctial seasons and winter for 1850–2005

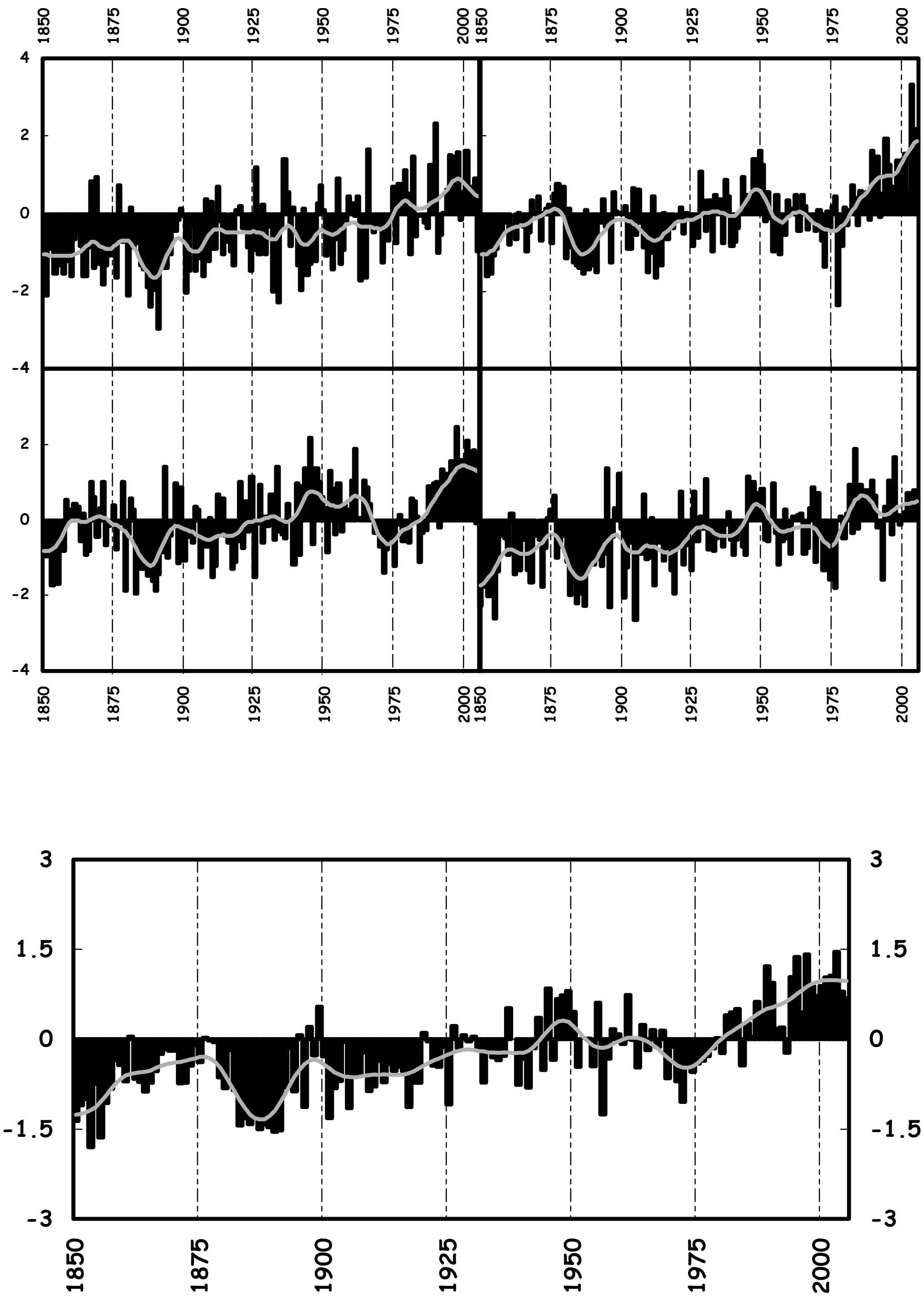

Figure 6. Annual and seasonal variations (1850–2005) of STS: daily mean temperatures expressed as anomalies (in °C) from 1961 to 1990 and smoothed with a 13-year Gaussian filter (thick line). Winter, top left. Summer, top right. Spring, bottom left. Autumn, bottom right.

and also by spring and autumn together with summer for 1901–2005.

[30] Our results are in disagreement with the findings documented [i.e., *Easterling et al.*, 1997] and reviewed by *Folland et al.* [2001] at the global scale for the second half of the twentieth century, which indicates higher increases for T_{min} than for T_{max} with a subsequent reduction in the global diurnal temperature range (DTR). However, this feature is not common to all regions, as some of them show the opposite behavior [*Folland et al.*, 2001], like that found over mainland Spain. Moreover, no statistically significant reduction of global DTR has recently been reported over the period 1979–2004 [*Vose et al.*, 2005]. In addition, and as stated in the introduction, similar findings (i.e., larger rates of change for T_{max} than for T_{min} records over the twentieth century) have been reported over the whole of Spain (*Brunet et al.*, [2001b] by using 96 monthly adjusted T_{max} and T_{min} records and *B*06 with the 22 daily adjusted records) and different Spanish subregions by various research teams, *Abaurrea et al.* [2001] over the middle Ebro River Basin using 21 T_{max} and T_{min} monthly adjusted records, *Brunet et al.* [2001d] over northeastern Spain with

Table 5. Seasonal and Annual Temperature Change Estimated by a Linear Trend and in Brackets the Associated 95% Confidence Intervals (in °C/Decade) for Daily Mean, Maximum, and Minimum Temperatures of STS Calculated Over the Entire Period and Several Shorter Periods of Warming and Cooling[a]

Periods	1850–2005	1901–2005	1901–1949	1950–1972	1973–2005
Daily Mean Temperatures					
Annual	**0.10** (0.08/0.12)	**0.13** (0.10/0.16)	**0.22** (0.11/0.31)	−0.19(−0.53/0.12)	**0.48** (0.36/0.66)
Winter	**0.10** (0.07/0.14)	**0.14** (0.08/0.20)	0.10 (−0.08/0.32)	0.11 (−0.58/0.68)	0.27 (−0.09/0.56)
Spring	**0.08** (0.05/0.12)	**0.12** (0.06/0.17)	**0.25** (0.06/0.43)	−0.52 (−1.03/0.05)	**0.77** (0.54/0.97)
Summer	**0.09** (0.06/0.11)	**0.13** (0.08/0.18)	**0.23** (0.07/0.38)	−0.29 (−0.71/0.13)	**0.67** (0.41/0.92)
Autumn	**0.10** (0.07/0.13)	**0.12** (0.08/0.17)	**0.26** (0.09/0.42)	−0.08 (−0.57/0.53)	*0.29* (0.02/0.58)
Daily Maximum Temperatures					
Annual	**0.11** (0.09/0.14)	**0.17** (0.13/0.21)	**0.37** (0.25/0.46)	−0.28 (−0.74/0.16)	**0.51** (0.34/0.66)
Winter	**0.12** (0.09/0.15)	**0.16** (0.10/0.21)	0.18 (−0.02/0.36)	−0.04 (−0.61/0.62)	*0.35* (0.06/0.60)
Spring	**0.11** (0.06/0.15)	**0.17** (0.11/0.23)	**0.37** (0.16/0.60)	−0.62 (−1.38/0.09)	**0.82** (0.53/1.15)
Summer	**0.10** (0.06/0.13)	**0.18** (0.12/0.24)	**0.44** (0.27/0.64)	−0.30 (−0.88/0.17)	**0.73** (0.43/1.04)
Autumn	**0.12** (0.09/0.15)	**0.17** (0.10/0.22)	**0.44** (0.26/0.64)	−0.12 (−0.84/0.70)	0.13 (−0.17/0.47)
Daily Minimum Temperatures					
Annual	**0.08** (0.06/0.10)	**0.09** (0.06/0.12)	0.08 (−0.02/0.18)	−0.13 (−0.51/0.14)	**0.47** (0.31/0.65)
Winter	**0.09** (0.06/0.13)	**0.12** (0.05/0.19)	0.06 (−0.15/0.24)	0.15 (−0.56/0.78)	0.06 (−0.28/0.62)
Spring	**0.07** (0.04/0.09)	**0.08** (0.03/0.13)	*0.15* (0.01/0.31)	−0.19 (−0.72/0.29	**0.66** (0.46/0.84)
Summer	**0.08** (0.05/0.10)	**0.09** (0.04/0.13)	0.00 (−0.13/0.14)	−0.26 (−0.60/0.08)	**0.62** (0.38/0.93)
Autumn	**0.08** (0.05/0.11)	**0.08** (0.04/0.13)	0.09 (−0.06/0.25)	−0.13 (−0.41/0.33)	**0.43** (0.18/0.77)

[a]Bold (italic) indicates significance at 1% (5%) confidence level.

23 records, *Galan et al.* [2001] over the southern Spanish plateau with 24 records, *Horcas et al.* [2001] over the Segura River Basin with 23 records, and *Morales et al.* [2005] over the northern Spanish plateau with 38 monthly adjusted T_{max} and T_{min} records. According to these studies, all records were quality controlled and homogenized by means of the SNHT [*Alexandersson and Moberg*, 1997] to detect and correct both potential abrupt shifts and artificial trends from the raw data.

3.2. Decadal Variability in the STS

[31] The decadal course of temperature change on an annual and a seasonal basis for the T_{mean} regional series (Figure 6) shows neither a stable nor a gradual increase in temperature. There are several episodes of rising and falling temperatures, as well as cold and warm phases, all clearly evident throughout the period analyzed. The strongest cold phase over the entire period was recorded during 1882–1892, which was 1.32°C colder than the 1961–1990 average for annual temperatures, being associated more with lower T_{max} than with T_{min} values (see Figure 6). This cold phase was mainly a result of cold autumns (−1.5°C) and winters (−1.4°C), followed by springs (−1.2°C) and summers (−1.05°C). These cold autumns were mainly related to very low daytime temperatures, but for winter the main contribution was from very cold nighttime temperatures. Finally, the cold springs and summers are more associated with colder days than nights (see Figure 7). The 1850s decade also shows low anomaly values, indicating that another cold phase took place then, but the reduced number of records available during this decade (two stations' records) makes its identification less reliable. Another cold phase also observed in the global and North Hemisphere curves [i.e., *Jones and Moberg*, 2003] during the second half of the twentieth century also took place over Peninsular Spain (between 1969–1978), for which anomalies (with respect to 1961–1990) of −0.47°C (annual), −0.63°C (autumn), −0.58°C (spring), −0.53°C (summer), and −0.19 (winter) have been calculated. On this occasion, winter had a negligible effect on this cold phase; instead it was mainly associated with low temperatures recorded by the equinoctial seasons and summers. In this case, T_{max} anomalies were lower than T_{min} anomalies, particularly because of the stronger contribution of day maximum temperatures in the autumn season (Figure 7). Only one moderate warm phase with positive anomaly averages occurred during the mid-twentieth century (centered on the 1943–1950 period). On an annual basis, this phase shows an average positive anomaly of 0.38°C (with respect to the 1961–1990 base period), which was mainly influenced by spring (0.85°C) and summer (0.74°C) and to a lesser extent by autumn (0.40°C). For winter, a negative average (−0.40°C) is evident, which indicates that winters of the 1940s were relatively cool. This feature has also been observed at larger spatial scales [*Jones and Moberg*, 2003],

Table 6. The Warmest and Coolest Monthly, Seasonal, and Annual Temperature Anomaly Values (in °C) in Daily T_{mean} STS Over the 1850–2005 Period

	Warmest		Coolest	
	Year	Highest, °C	Year	Lowest, °C
Jan	1955	2.6	1885	−3.7
Feb	1990	3.4	1956	−6.0
Mar	2001	3.6	1925	−3.5
Apr	1945	4.2	1986	−2.7
May	1964	3.3	1984	−3.4
Jun	2003	4.6	1909	−3.0
Jul	1994	2.4	1977	−2.7
Aug	2003	3.6	1896	−2.8
Sep	1987	2.7	1860	−4.1
Oct	1899	2.5	1887	−4.3
Nov	1983	2.7	1896	−3.1
Dec	1989	3.4	1871	−4.0
DJF[a]	1990	2.3	1891	−3.0
MAM[b]	1997	2.4	1883	−2.0
JJA[c]	2003	3.3	1977	−2.4
SON[d]	1983	1.9	1905	−2.6
Year	2003	1.5	1853	−1.8

[a]December, January, February; dated by the year of January.
[b]March, April, May.
[c]June, July, August.
[d]September, October, November.

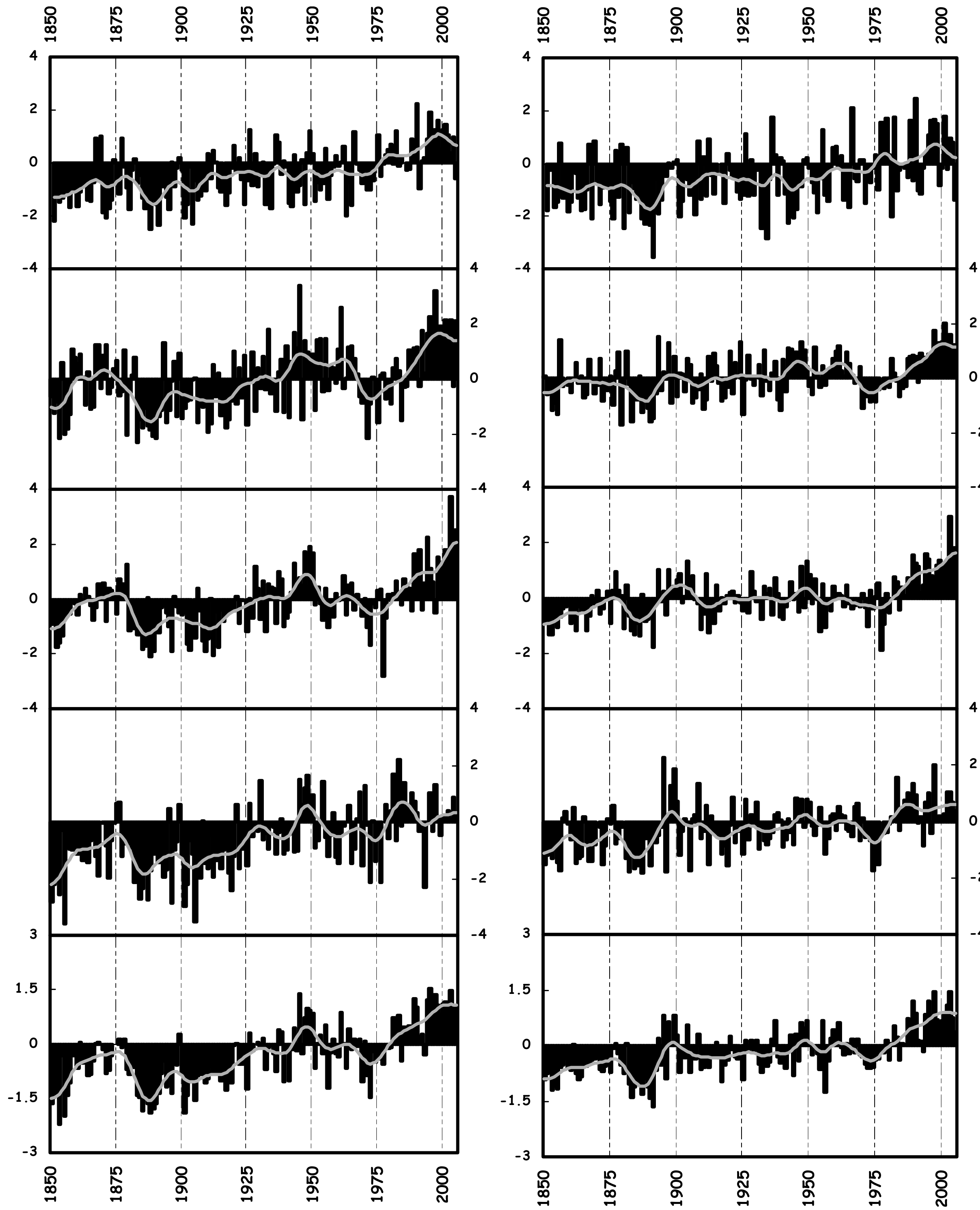

Figure 7. Same as Figure 6 but for daily maximum (left panel) and minimum (right panel) regional-averaged time series. From top to bottom: winter, spring, summer, autumn, and annual time series.

although its peak for the NH was in the early 1940s. Higher daytime than nighttime temperatures on the annual scale in spring, summer, and autumn have contributed most to this warming phase (Figure 7).

[32] The temporal evolution highlighted by the smoothed annual curve also shows two main episodes of rising temperatures, the early and late twentieth century warming episodes, and one subperiod of falling temperatures, between 1948 and 1973. The first period of warming took place between 1901 and 1949. Annual and seasonal (except winter) trends fitted over the 1901–1949 period are significant (see Table 5 for details). Annual warming was influ-

enced slightly more by the equinoctial seasons followed by similar rates for summer, with winter having the smallest and nonsignificant contribution. Daytime temperatures contributed more to this increase: T_{max} trends are significant but T_{min} are not (Table 5). A short period of falling temperatures has been identified from 1950 to 1972, in agreement with that recorded at larger global and hemispherical scales [*Jones and Moberg*, 2003]. However, the trends both on an annual and a seasonal basis are nonsignificant in the three daily temperature series (Table 5). Spring and summer were the seasons with the largest decreases that led to the reduction in annual temperatures. Autumn contributed a little, while winter was the season with only a slight and nonsignificant positive trend (Table 5).

[33] The latest 1973–2005 episode of accelerated warming is the period that has the highest rates of change among the three subperiods both on an annual and a seasonal basis and for all daily temperature variables, except for T_{max} in autumns and T_{min} in winters (Table 5). Annual average warming was mainly the result of spring and summer warming, while autumn and winter have contributed less to this warming, and moreover, winter trends do not reach the statistical significance level (0.05) in the T_{mean} series. The larger spring and summer contribution to the increases in annual temperatures in all three Spanish curves highlights the key role played by the warm seasons and should be the focus of further studies on the possible attribution of anthropogenically induced regional warming. Similar twentieth century variations have been found by other researchers over mainland Spain [*Brunet et al.*, 2001a; *Rodríguez-Puebla et al.*, 2002; *Esteban-Parra et al.*, 2003a, 2003b] and for different subregions: northeastern Spain [*Brunet et al.*, 2001c], the middle Ebro River Basin [*Abaurrea et al.*, 2001], Southern Spanish Plateau [*Galan et al.*, 2001], Segura River Basin [*Horcas et al.*, 2001], and Northern Spanish plateau [*Morales et al.*, 2005]. Agreement in neighboring countries has also been reported, over France by *Abarca del Río and Mestre* [2006] and over Italy by *Brunetti et al.* [2006].

4. Spatial Patterns of Long-Term Temperature Change

[34] As indicated in section 2.2, an RPCA of the 22-station daily mean temperature data set has been carried out on an annual, seasonal, and monthly basis in order to characterize the most prominent spatial modes of variability of Spanish long-term temperature change (1901–2005).

[35] The analysis yields three rotated principal components (RPCs) that are identified both on an annual (Figure 8) and a seasonal basis (Figures 9–12), except for winter where only two spatial modes of variability are significant (Figure 9). These components define three spatial patterns that explain the bulk of the long-term Spanish temperature change on an annual, spring, summer, and autumn basis: Northern Spain pattern (NS), Southeastern and Eastern Spain pattern (SEES), and Southwestern Spain pattern (SWS). This result is in complete agreement with the study of *Oñate and Pou* [1996] where the same spatial patterns are defined and in partial agreement with the findings of the study of *Esteban-Parra et al.* [2003a] on long-term temperature variability and trends over Spain. These authors employed a nonrotated PCA approach, which identified a simpler spatial pattern of Spanish temperature variability (western and eastern parts of Spain) across the year. For winter, only one pattern was identified.

[36] Table 7 shows the eigenvalues and associated variance of the RPCs of annual and seasonal averages of daily mean temperature. These three RPCs explain 90.2% of the total variance on an annual basis, 88.4% (winter, only two RPCs), 91.1% (spring), 86.9% (summer), and 89.2% (autumn) in the 105 years of the Spanish temperature data set. Table 8 gives annual and seasonal subregional trends and their associated 95% confidence intervals (in °C/decade) for the three spatial patterns clustered by RPCA over the whole period and the identified subperiods. These have been calculated using the individual anomaly time series (with respect to the 1961–1990 base period) of those stations in each of the regions whose loading $\geq$0.60.

[37] On an annual basis, the first RPC illustrates the NS pattern, which describes coherent temperature variability over the northernmost third of Spain (Figure 8a). Influences from southern Spain are small. This Spanish subregion is mainly influenced from the North Atlantic. The estimated significant annual trend is 0.13 (0.09/0.16) °C/decade (Table 8). The main feature of the long-term temperature variations is the large contribution made to the shape of the first episode of rising temperatures (1901–1949) in the STS. Warming in the recent period is remarkable as well. Also, this area impacts the warm phase of the mid-1940s, as well as the cold phase of the 1970s.

[38] The second RPC identifies the SEES pattern, with the highest loadings over the southeasternmost third of the IP, also including the entire Spanish Mediterranean coastal areas and having its lowest loadings over western parts of Spain (Figure 8b). Because of its location, it is a pattern particularly influenced by the Mediterranean Sea. The annual significant trend over 1901–2005 is 0.13 (0.09/0.16) °C/decade, which is mainly due to the strong rise in temperatures from 1973–2005 over this region. This pattern's contribution to the configuration of the warm and cold twentieth century phases is more modest, as well as to the first episode of rising temperatures (Figure 8b and Table 8). Further research on exploring the relationships between SSTs in the Mediterranean and this pattern is necessary to improve understanding of the influence of SSTs on long-term temperature change over Spain, particularly during the last episode of accelerated warming.

[39] The third RPC illustrates the SWS pattern, which describes temperature variability centered over the southwestern third of Spain with loadings decreasing toward the northeast part of the IP (Figure 8c). This pattern has the highest annual [0.14 (0.11/0.18) °C/decade] significant trend over the entire period. It has also strongly contributed to the shape of the first episode of increasing temperatures leading to the midtwentieth century-centered warm phase. This pattern has also contributed most to the cold phase of the 1970s, with a significant (at the 0.05 level) negative trend on annual basis (Figure 8c and Table 8).

[40] All three spatial modes of Spanish temperature variability on an annual basis show large and significant trends, although the SWS pattern reaches greater rates of change than NS and SEES over the twentieth century. The

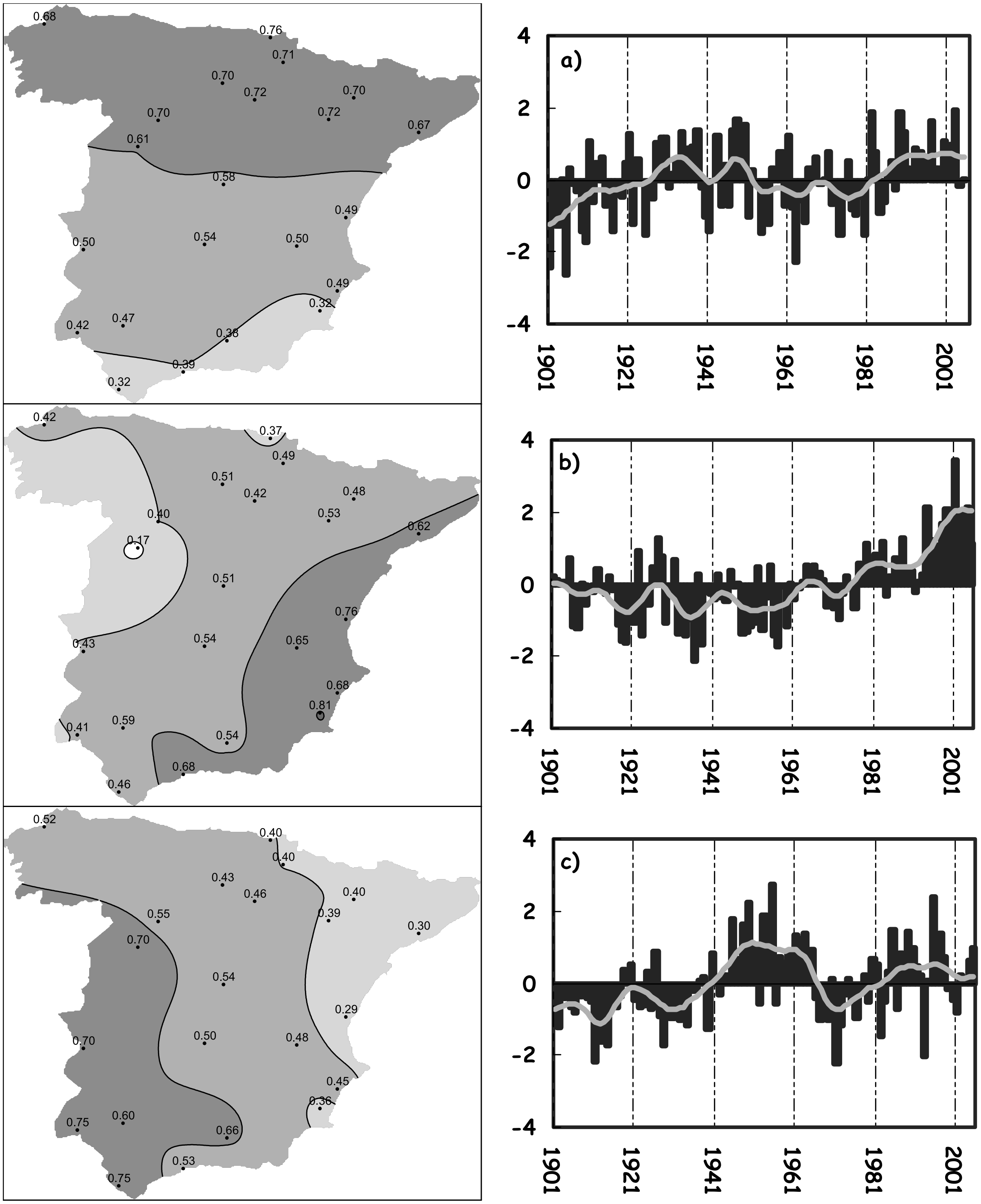

Figure 8. Loading factor maps and the associated score series for the (a) first, (b) second, and (c) third RPCA resulting from the analysis of the annual temperatures during 1901–2005, identifying the NS, SEES, and SWS patterns, respectively (see text for details).

RPCs estimated on a seasonal basis indicate a slightly different temporal evolution of warming with respect to the spatial patterns obtained. When looking at this scale, the strongest contribution to the estimated seasonal trends in the STS (Table 8) is evident in the SWS and NS patterns during winter and summer and in the SEES pattern for spring, while the Spanish autumn trends can be attributed to similar rates of change for the three patterns over the 1901–2005 period.

[41] Winter Spanish warming has been slightly more influenced by the SWS area than by the NS region (Figure 9 and Table 8). For spring and summer, the SWS

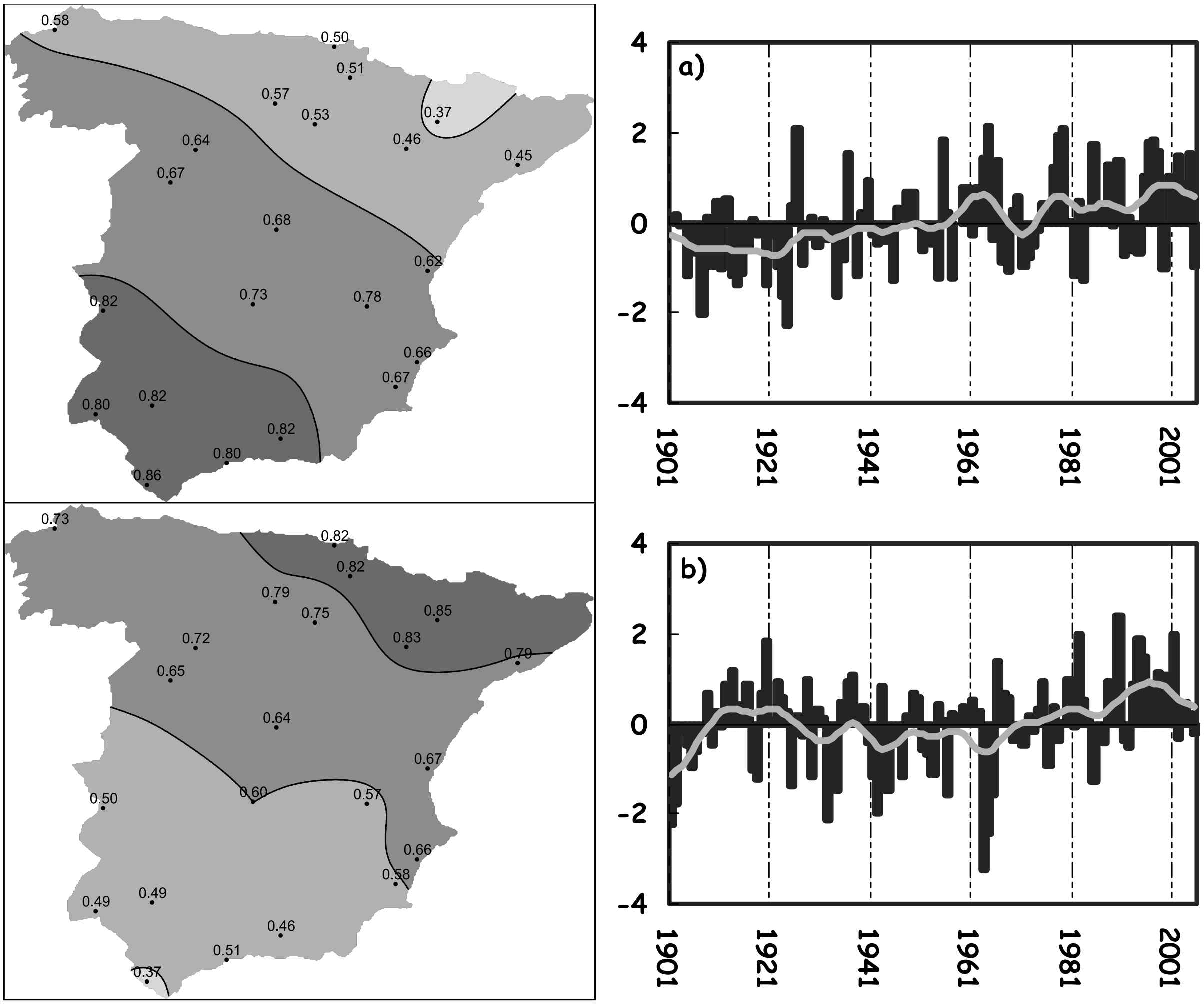

Figure 9. Same as Figure 8 but for winter. (a) SWS pattern and (b) NS pattern (see text for details).

pattern explains the highest variance of the Spanish temperature data set, followed by the NS pattern and the SEES pattern with the lowest explained variance (Table 7 and Figures 10 and 11). The variance explained for autumn has been slightly higher over the NS and SWS areas than over the SEES region (Table 7 and Figure 12). However, for spring, the highest and significant trends have been estimated over SWS and SEES regions and to lesser extent over the NS areas (Table 8).

[42] The early twentieth century episode of increasing temperatures (1901–1949) was more the result of warming of the NS region and to a lesser extent over the SWS region than over the SEES area on an annual scale. Autumn and spring were the seasons with the highest contributions to the annual increases, with summer showing strong positive rates of change over both the NS and SWS regions (Table 8). The cold period of 1950–1972 was due more to the contribution from the reduction in temperatures over SWS region than over the NS and SEES areas, with summer (spring) showing the highest negative trends over the SWS (NS) patterns (Table 8).

[43] For the last episode of warming (1973–2005), the SWS and SEES patterns contributed most to the annual trends in the T_{mean} regional series (Table 8). On a seasonal basis, the most striking feature has been the shift observed in seasonal trends, which has led to higher rates of change estimated for spring and summer in the three patterns (higher in spring over the SWS and NS patterns than in the SEES pattern, while for summer is slightly larger over the SEES pattern). Finally, the largest and most significant autumn trends have been estimated for SEES (Table 8), emphasizing the potential role that an overheated Mediterranean sea surface might be playing during this season, a topic that deserves further attention.

5. Assessment of Long-Term Changes in the Occurrence of Temperature Extremes

[44] In order to address the nature of changes in the mean state of the Spanish climate and document how the long-term temperature change has developed, a preliminary assessment of long-term changes in extreme temperature occurrences has been made using the RClimDex software package [*Zhang and Yang*, 2004] on an annual basis and with the EMULATE extreme indices software [*Walther*, 2004] on seasonal scales. These approaches consider trends in some core percentile-based ‘‘extreme temperature indices’’ obtained from the list of climate change indices recommended by the Expert Team on Climate Change Detection, Monitoring and Indices [CCI/CLIVAR ETCCDMI http://

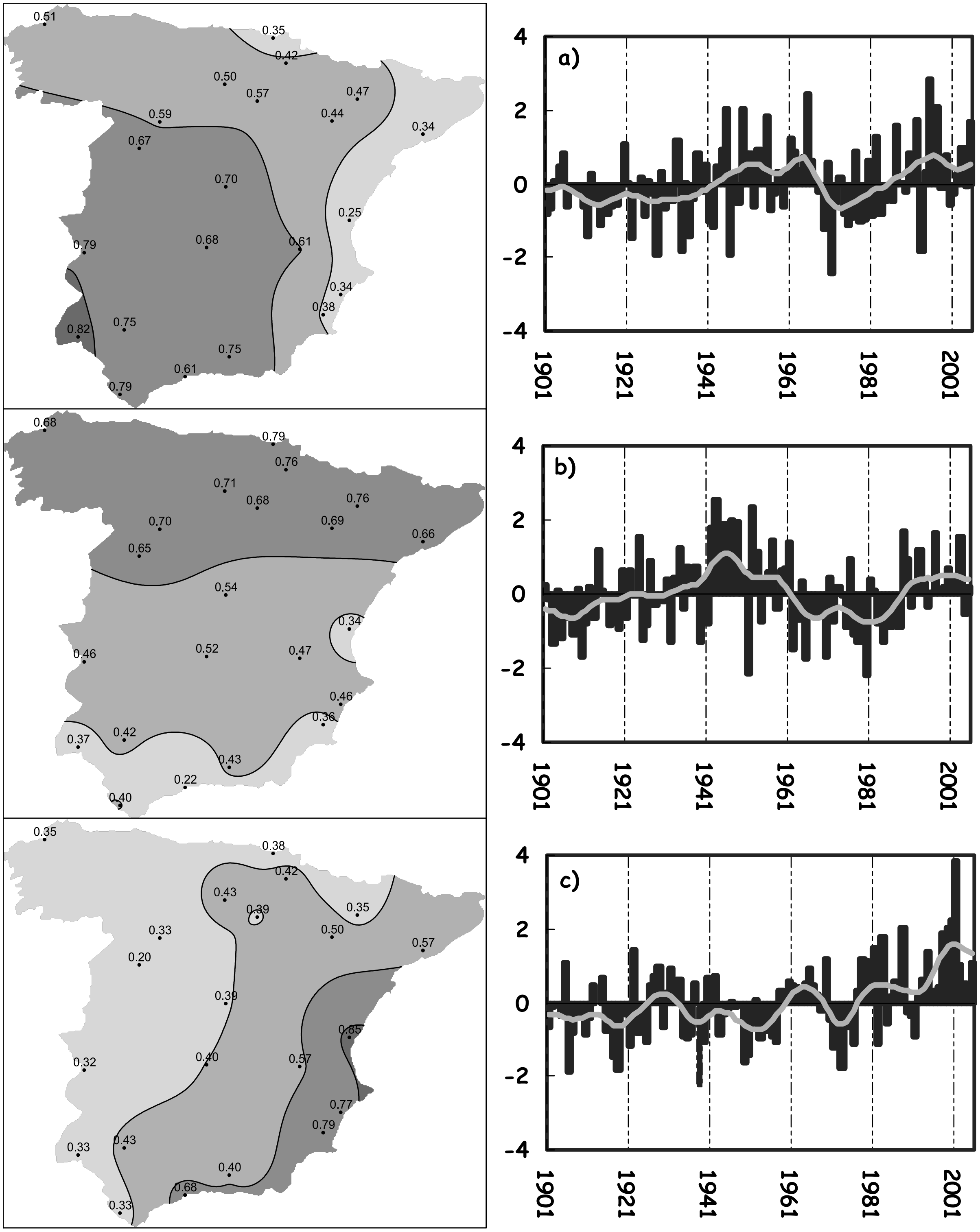

Figure 10. Same as Figure 8 but for spring. (a) SWS pattern, (b) NS pattern, and (c) SEES pattern (see text for details).

www.clivar.org/organization/etccd)] of the World Meteorological Organization-Commission for Climatology and the research programme of CLIVAR and from EMULATE core-percentile based extreme indices http://www.cru.uea.ac.uk/cru/projects/emulate/public/EMULATE-INDICES-SOFTWARE.doc). Analysis of annual and seasonal exceedances of daily T_{max} and T_{min} 10th and 90th percentiles calculated with respect to the 1961–1990 baseline period, which describe the number of moderately extreme cold days and nights and moderately extreme warm days and nights, respectively, have been studied for the entire period (1850–2005) and also for the other identified subperiods

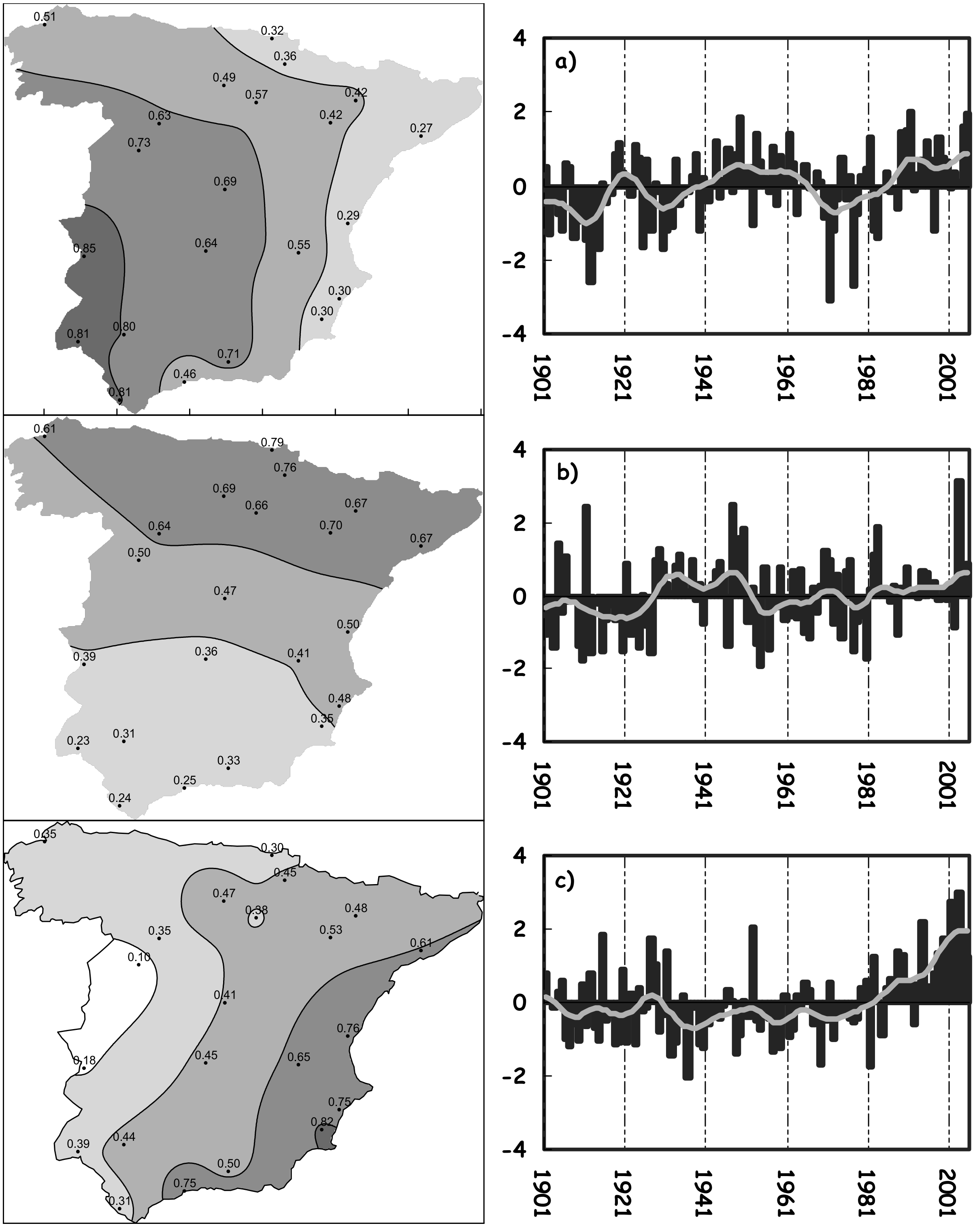

Figure 11. Same as Figure 8 but for summer. (a) SWS pattern, (b) NS pattern, and (c) SEES pattern (see text for details).

in section 3. An RPCA for documenting spatial patterns of Spanish long-term change in extreme temperatures has also been carried out for the shorter period of 1901–2005, when all 22 series are complete enough to calculate indices through time. Other shorter and more recent subperiods can be compared with our results over Spain and findings reported by other researchers [*Frich et al.*, 2002; *Yan et al.*, 2002; *Klein Tank and Können*, 2003; *Mokssit*, 2003; *Della-Marta et al., submitted manuscript*, 2006] at larger spatial scales.

[45] The RClimDex and EMULATE software have been used with the 22 daily adjusted records of $T_{\max}$ and $T_{\min}$ to

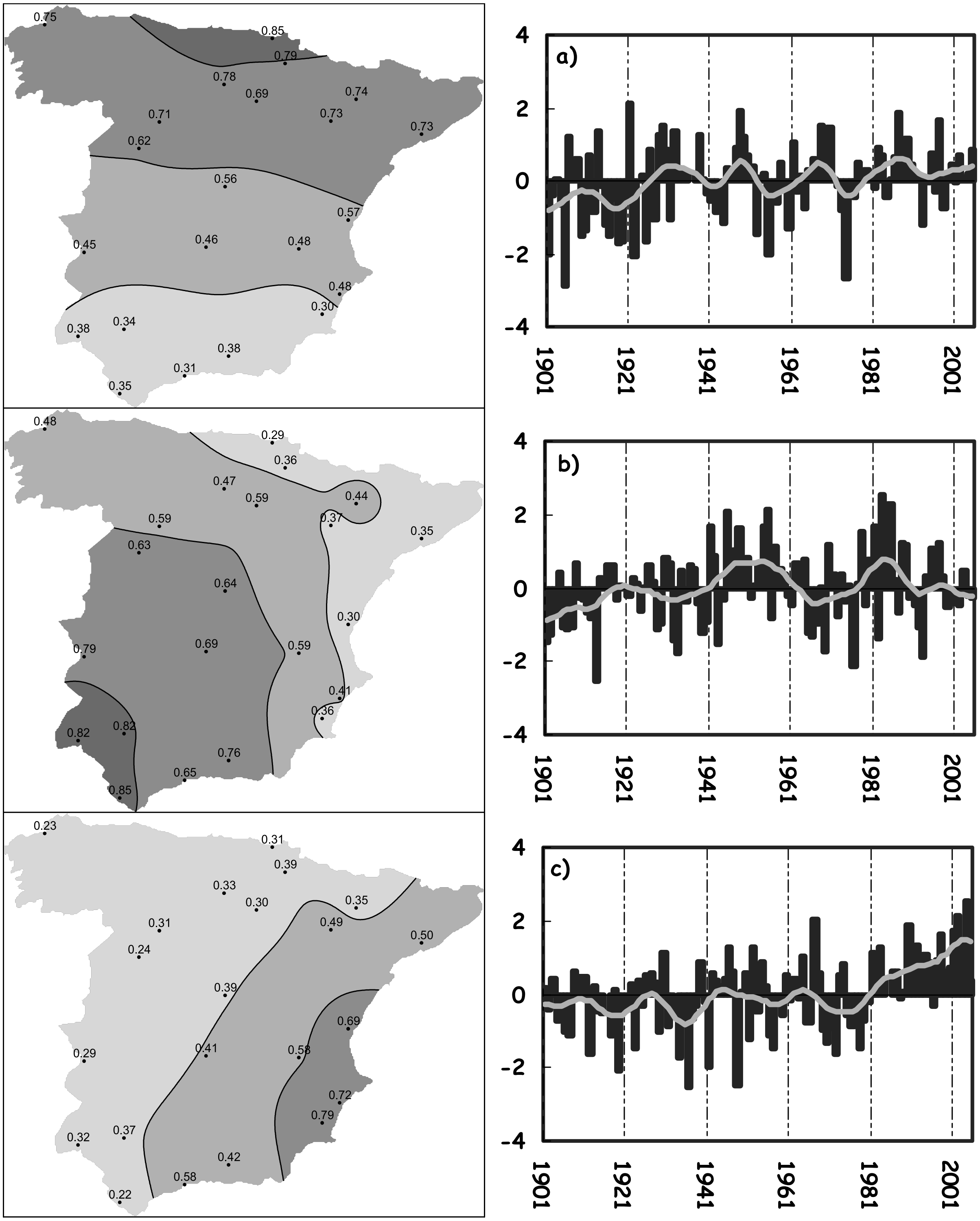

Figure 12. Same as Figure 8 but for autumn. (a) NS pattern, (b) SWS pattern, and (c) SEES pattern (see text for details).

develop the annual and seasonal indices' time series. Regional Spanish time series of temperature extreme indices have also been constructed by averaging all the records and using the simple weighting algorithm described by *Jones and Hulme* [1996] (not shown). Table 9 shows rates of change estimated from time series of Spanish area-averaged changes in the four percentile-based indices over the different periods. The most consistent and coherent temporal signal emerging from the trends of the four extreme temperature indices selected indicates that Spanish warming has principally been associated with a large and significant reduction in the number of "moderately extreme cold days" (T_{max} < 10th percentile) and to a lesser extent to "moderately extreme cold nights" (T_{min} < 10th percentile) for the

Table 7. Eigenvalues and Variance Explained by the Rotated Principal Components of Daily Mean Temperature on an Annual and a Seasonal Basis

	NS Pattern		SEES Pattern		SWS Pattern	
	Eigenvalue	% Variance	Eigenvalue	% Variance	Eigenvalue	% Variance
Annual	7.39	33.58	6.41	29.14	6.04	27.48
Winter	9.69	44.05	–	–	9.77	44.39
Spring	7.21	32.78	5.32	24.17	7.51	34.15
Summer	6.20	28.17	5.69	25.85	7.24	32.93
Autumn	7.71	35.03	4.42	20.10	7.50	34.09

whole period (1850–2005). This result is in agreement with the statement of *Alexander et al.* [2006] that "rather than viewing the world as getting hotter it might be more accurate to view it as getting less cold". Trends of "moderately extreme warm days and nights" (T_{max} and T_{min} > 90th percentile) have not changed as much but indicate that warm days have increased slightly more than warm nights over the 1850–2005 period, also reaching significant trends. Consequently, averaged over Spain, there were 11.5 (8.4) fewer moderately extreme cold days (moderately extreme cold nights) in the year 2005 than in 1850, as well as 8.3 (7.6) more "moderately extreme warm days" (moderately extreme warm nights) in the year 2005 than in 1850 (Table 9). These results are in disagreement with findings reported at larger scales, global [*Frich et al.*, 2002; *Alexander et al.*, 2006] or Europe [*Klein Tank and Können*, 2003; *Yan et al.*, 2002], where the largest rates of positive change have been established for moderately warm nights mainly during the second half of the twentieth century. However, *Mokssit* [2003] found similar results over southern Spain in his study of long-term temperature and precipitation change over Africa during the second half of the twentieth century, and Della-Marta et al. (submitted manuscript, 2006) found similar results from 1880 to 2005 using the same data as employed in this study.

[46] Trends in extreme temperature indices for shorter periods have also been calculated for the episodes identified in section 3 with warming and cooling trends in STS (Table 9). For the second half of the nineteenth century, although the number of available station records dramatically decays during the earliest decades making series less representative of the whole of peninsular Spain, only the "moderately extreme warm nights" index shows a positive trend reaching statistical significance. The annual trend was contributed to by higher increases in summer, autumn, and to a lesser extent in winter than in spring. Occurrences of "moderately extreme cold days and nights," as well as moderately extreme warm days, show reductions on an annual and a seasonal basis over that period, but they are not significant, except for winter (summer) with a negative (positive) trend at the 0.05 significance level for moderately extreme cold days (Table 9). When looking at the three twentieth-century subperiods of rising and falling temperatures, it is clear that only the warming episodes show significant trends. The early twentieth century temperature rise over Spain was mainly accompanied by stronger and significant reductions (increases) in moderately extreme cold days (moderately extreme warm days), both on an annual and a seasonal basis (particularly remarkable are the reductions in the occurrence of extremely cold days during summer, spring, and autumn). The contribution to this episode of moderately extreme cold and warm nights is almost negligible, as only a significant (at the 0.05 level) negative trend has been estimated for cold nights during spring (Table 9). For the cold episode between 1950 and

Table 8. Annual and Seasonal Trends and in Brackets the Associated 95% Confidence Intervals (in °C/Decade), for Daily Mean Temperature of the Three Clustered Regions by the RPCAs Calculated Over the Entire Period and Several Shorter Periods of Warming and Cooling and Using Those Stations Comprising Each Spatial Pattern With Loading ≥0.60[a]

Periods	1901–2005	1901–1949	1950–1972	1973–2005
Northern Spain (NS) Pattern				
Annual	**0.13** (0.09/0.16)	**0.25** (0.13/0.34)	−0.20 (−0.57/0.14)	**0.51** (0.36/0.69)
Winter	**0.14** (0.08/0.21)	0.12 (−0.09/0.33)	0.09 (−0.59/0.80)	0.26 (−0.12/0.58)
Spring	**0.11** (0.05/0.17)	**0.29** (0.10/0.48)	*−0.74* (−1.25/−0.11)	**0.77** (0.51/1.01)
Summer	**0.13** (0.08/0.18)	**0.24** (0.08/0.40)	−0.17 (−0.72/0.27)	**0.63** (0.36/0.95)
Autumn	**0.12** (0.06/0.17)	**0.29** (0.11/0.47)	−0.04 (−0.59/0.57)	*0.28* (0.04/0.66)
Southeastern and Eastern Spain (SEES) Pattern				
Annual	**0.13** (0.09/0.16)	**0.13** (0.04/0.22)	−0.14 (−0.50/0.20)	**0.54** (0.38/0.68)
Winter	–	–	–	–
Spring	**0.13** (0.07/0.18)	0.14 (−0.00/0.31)	−0.29 (−0.68/0.45)	**0.71** (0.45//0.97)
Summer	**0.12** (0.08/0.17)	0.12 (−0.01/0.22)	−0.24 (−0.69/0.12)	**0.69** (0.49/0.97)
Autumn	**0.12** (0.08/0.16)	*0.16* (0.03/0.30)	−0.19 (−0.72/0.33)	**0.39**(0.16/0.64)
Southwestern Spain (SWS) Pattern				
Annual	**0.14** (0.11/0.18)	**0.22** (0.13/0.29)	*−0.33* (−0.75/−0.03)	**0.55** (0.44/0.69)
Winter	**0.15** (0.09/0.21)	0.15 (−0.04/0.31)	0.11 (−0.52/0.56)	0.31 (−0.05/0.68)
Spring	**0.12** (0.06/0.18)	*0.24* (0.06/0.42)	−0.46 (−1.06/0.09)	**0.79** (0.46/1.05)
Summer	**0.13** (0.07/0.18)	**0.24** (0.08/0.40)	*−0.48* (−0.81/−0.09)	**0.65** (0.34/0.96)
Autumn	**0.12** (0.07/0.17)	**0.28** (0.12/0.45)	−0.35 (−0.84/0.35)	0.18 (−0.13/0.54)

[a]Bold (italic) indicates significance at 1% (5%) confidence level (see text for details on trend calculation for each spatial pattern).

Table 9. Annual and Seasonal Trends (in Brackets the Associated 95% Confidence Interval) in Days per Decade for Four Percentile-Based Temperature Extreme Indices for Several Periods for the SDATS[a]

Periods	1850–2005	1850–1900	1901–1949	1950–1972	1973–2005
T_{max} < 10th Percentile					
Annual	**−0.74** (−0.87/−0.61)	−0.62 (−1.51/0.30)	**−1.89** (−2.47/−1.27)	1.70 (−0.69/3.63)	**−2.04** (−2.89/−1.22)
Winter	**−0.78** (−1.00/−0.56)	*−1.96* (−3.34/−0.23)	−0.03 (−1.06/1.16)	−2.36 (−4.84/1.13)	−0.66 (−1.79/0.65)
Spring	**−0.52** (−0.71/−0.35)	0.28 (−0.86/1.54)	**−2.15** (−3.14/−1.38)	2.56 (−0.10/5.77)	**−2.14** (−3.01/−1.31)
Summer	**−0.43** (−0.61/−0.25)	*1.28* (0.17/2.42)	**−2.32** (−3.19/−1.36)	1.28 (−1.10/4.15)	**−2.24** (−3.66/−0.84)
Autumn	**−0.78** (−0.98/−0.61)	−1.29 (−2.71/0.25)	**−2.01** (−3.00/−1.06)	2.74 (−0.17/6.07)	*−1.33* (−2.81/−0.01)
T_{max} > 90th Percentile					
Annual	**0.53** (0.39/0.67)	−0.47 (−1.20/0.56)	**1.51** (0.97/2.10)	−0.76 (−3.35/1.37)	**3.11** (2.09/3.97)
Winter	**0.55** (0.41/0.67)	0.10 (−0.55/0.83)	**0.99** (0.33/1.67)	−0.83 (−3.77/1.11)	0.85 (−0.96/2.29)
Spring	**0.48** (0.29/0.68)	0.07 (−0.97/1.00)	*1.26* (0.11/2.31)	−2.29 (−6.30/1.68)	**4.00** (2.49/5.57)
Summer	**0.49** (0.32/0.66)	−0.16 (−1.33/0.82)	**1.85** (1.02/2.64)	*−1.69* (−3.35/−0.41)	**4.77** (3.09/6.34)
Autumn	**0.36** (0.22/0.51)	−0.03 (−1.00/0.60)	**1.41** (0.81/2.14)	0.51 (−2.85/4.05)	0.79 (−1.04/2.21)
T_{min} < 10th Percentile					
Annual	**−0.54** (−0.68/−0.40)	−0.12 (−1.23/1.12)	−0.25 (−0.95/0.48)	0.75 (−1.59/2.94)	**−2.70** (−3.55/−1.83)
Winter	**−0.59** (−0.83/−0.35)	−0.16 (−1.89/1.47)	0.30 (−0.69/1.53)	−2.81 (−6.99/2.15)	−0.15 (−1.90/1.69)
Spring	**−0.31** (−0.47/−0.16)	0.43 (−0.62/1.65)	*−0.89* (−1.65/−0.20)	0.89 (−1.66/4.08)	**−2.12** (−3.06/−1.30)
Summer	**−0.42** (−0.58/−0.27)	−0.55 (−1.70/0.36)	0.18 (−0.67/0.94)	1.17 (−2.06/4.05)	**−1.82** (−3.08/−0.76)
Autumn	**−0.44** (−0.64/−0.26)	0.07 (−1.46/1.39)	−0.11 (−0.91/0.77)	1.28 (−1.33/3.27)	**−2.19** (−3.63/−1.15)
T_{min} > 90th Percentile					
Annual	**0.49** (0.36/0.62)	**1.08** (0.32/1.83)	0.25 (−0.24/0.82)	−1.00 (−3.02/1.02)	**3.74** (2.60/5.18)
Winter	**0.37** (0.23/0.53)	*0.67* (0.07/1.46)	0.29 (−0.40/0.97)	−1.50 (−4.90/1.42)	−0.35 (−2.15/2.19)
Spring	**0.45** (0.29/0.63)	0.38 (−0.22/1.26)	0.60 (−0.38/1.64)	−0.63 (−4.05/1.52)	**4.37** (3.05/5.95)
Summer	**0.51** (0.31/0.72)	**1.64** (0.71/2.56)	−0.05 (−0.96/0.87)	−1.87 (−4.17/0.30)	**6.86** (4.54/9.04)
Autumn	**0.37** (0.23/0.52)	**1.47** (0.76/2.27)	0.66 (−0.16/1.25)	−0.03 (−2.43/2.40)	**2.58** (0.74/4.18)

[a]Bold (italic) indicates significance at 1% (5%) confidence level.

1972 over Spain, cooling is associated with annual and seasonal increases (reductions) of moderately extreme cold days and nights (warm days and nights), although their trends are nonsignificant at the adopted level (0.05), except for summer T_{max} > 90th percentile. Our results are in agreement with the sign and rates of trends calculated over Europe by *Klein Tank and Können* [2003]. For the final episode of warming, a shift in the occurrence of temperature extremes and its contribution to Spanish warming compared to that observed over the entire period or across the twentieth century can be clearly seen. Spanish warming is mainly associated with higher increases in moderately extreme warm nights and days than with reductions of moderately extreme cold nights and days at both annual and seasonal scales (Table 9). So over Spain in this accelerated episode of recent warming, the country is getting hotter as opposed to less cold. Annual counts of moderately extreme warm night and day occurrences have mainly been the result of the increasing contribution of summers and springs. These results are again in agreement with findings over Europe reported by Klein Tank and Können for a similar period.

[47] In order to assess spatial differences in the rate of twentieth-century change in extreme temperature occurrences across Spain for the period 1901–2005, an RPCA has been run on an annual basis with the resulting indices (22 × 4 = 88 time series). Three spatial patterns have also been isolated from the RPCA approach (through the 22 time series of moderately extreme cold day indices), explaining 78.5% of total variance. These patterns present clear similarities to those estimated for the Spanish long-term temperature change described in section 4: a slight variant of the NS pattern (with the 37% of the total variance explained) as it integrates most of north-northwestern and central Spain but omitting the northeasternmost third part of Spain and with a significant trend of −0.76 (−0.97/−0.56) days/decade; the SEES pattern (21.5%), again a slight variant of it more centered over the Eastern than Southeastern Spanish Mediterranean coast with the highest significant trend of −0.91 (−1.13/−0.66) days/decade; and the SWS pattern (20%), which has seen the second largest reduction of −0.81 (−1.01/−0.61) days/decade, significant at the 0.01 level. Figures 13a–13c depict these patterns and the associated score series for cold days. The trends estimated from the time series comprised each pattern with a loading ≥0.60 indicate that the largest reductions have been associated with the SEES and SWS patterns. Seasonal rates of change for this and the other percentile-based indices are shown in Table 10. For the SEES pattern, which had the highest trend among the three spatial patterns and four indices, summer has been the season that has most strongly contributed to the annual decrease in moderately extreme cold days, followed by autumn and to a lesser extent by spring. For the NS pattern, summer and spring have reached the highest rates of change, with autumn and winter contributing slightly less to the annual reductions. Finally, over the SWS region, autumn, spring, and winter are the seasons with the greater reductions, while summer has contributed only moderately.

[48] Moderately extreme warm days have also reached similar significant positive rates of change for the three spatial patterns estimated (Figure 14), which explain 79% of total cumulative variance of this time series and show consistent positive trend coefficients; the first RPCA shows another slight variant of the NS pattern, which accounts for 29% of the total variance (Figure 14a), with a positive trend of 0.81 (0.59/1.04) days/decade and the SWS [27%, 0.86 (0.61/1.09) days/decade, Figure 14b] and the SEES [23%, 0.72 (0.50/0.93) days/decade, Figure 14c] patterns. Therefore the SWS and NS patterns have contributed

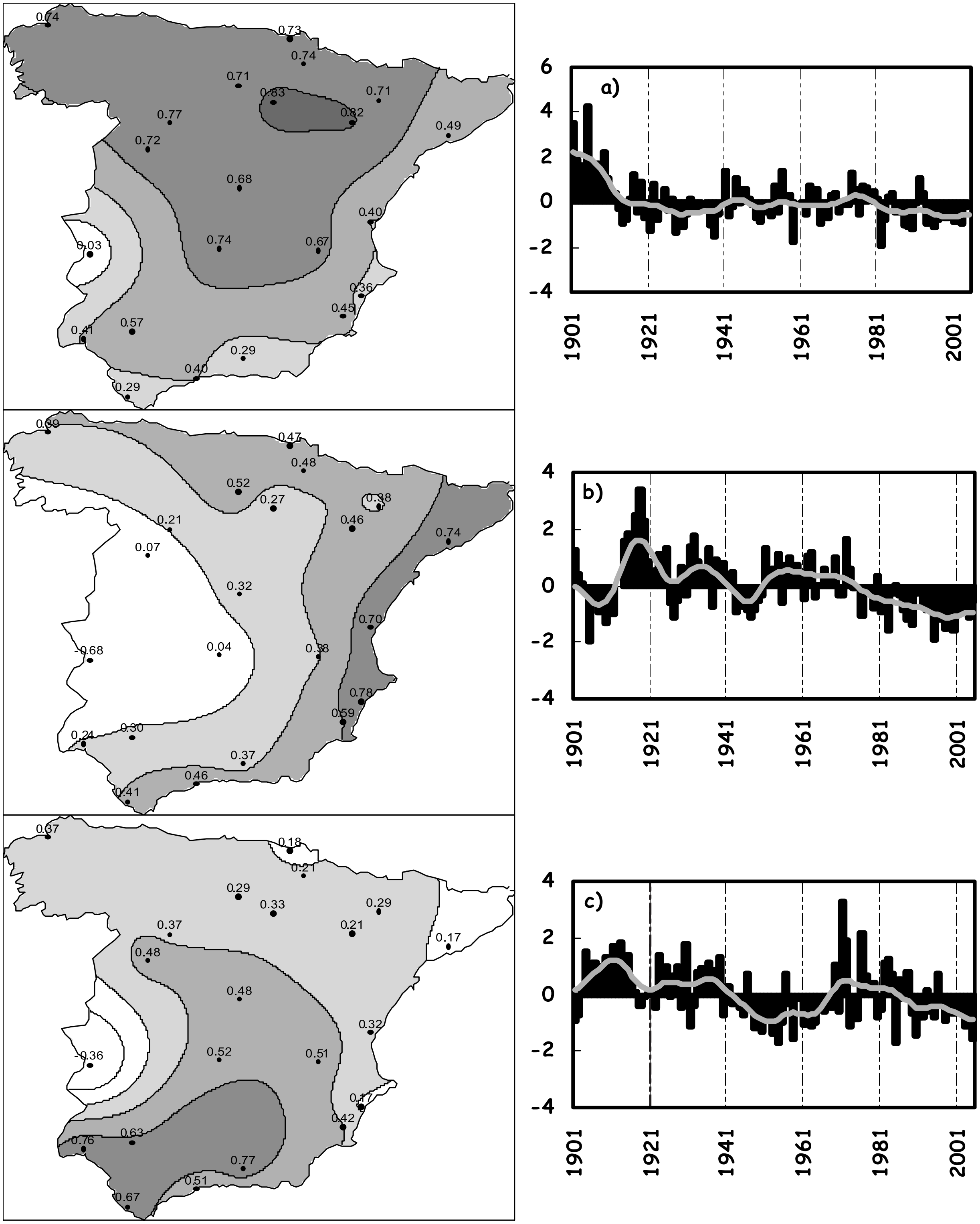

Figure 13. Same as Figure 8 but for annual counts of days not exceeding the T_{max} < 10th percentile threshold (in days/decade). (a) NS pattern, (b) SEES pattern, and (c) SWS pattern (see text for details).

slightly more than the SEES pattern to Spanish increases in moderately extreme warm days. On a seasonal basis, winter and spring show greater increases than summer and autumn in the counts of warm days over the SWS region, while over the NS pattern, summer, followed by spring and winter, has seen the greatest rates of change, with autumn contributing a little. The SEES pattern has the peculiarity of presenting larger increases during summer and autumn, with spring contributing more moderately. This is the only pattern that shows autumns contributing more to the annual increases of this index. All seasonal trends are statistically significant (Table 10).

Table 10. Seasonal Trends (in Days per Decade) for the Period 1901–2005 of "Moderately Extreme Cold Days" (T_{max} < 10th Percentile), "Moderately Extreme Warm Days" (T_{max} > 90th Percentile), "Moderately Extreme Cold Nights" (T_{min} < 10th Percentile), and "Moderately Extreme Warm Nights" (T_{min} > 90th Percentile) Indices for the Three Spatial Patterns (Clustered by the RPCA of the Daily T_{max} and T_{min} Time Series Using Those Stations Comprising Each Spatial Pattern With Loading $\geq$0.60)[a]

Periods	T_{max} < 10th Percentile	T_{max} > 90th Percentile	T_{min} < 10th Percentile	T_{min} > 90th Percentile
Northern Spain (NS) Pattern				
Winter	**−0.57** (−0.92/−0.22)	**0.59** (0.37/0.83)	*−0.30* (−0.66/0.00)	**0.43** (0.14/0.79)
Spring	**−0.63** (−0.92/−0.33)	**0.66** (0.27/1.07)	−0.18 (−0.43/0.07)	*0.39* (0.08/0.73)
Summer	**−0.65** (−0.96/−0.36)	**0.84** (0.49/1.17)	**−0.41** (−0.67/−0.18)	*0.50* (0.11/0.90)
Autumn	**−0.61** (−0.90/−0.35)	**0.45** (0.18/0.72)	−0.22 (−0.49/0.01)	**0.47** (0.21/0.71)
Southeastern and Eastern Spain (SEES) Pattern				
Winter	–	–	–	–
Spring	**−0.68** (−1.02/−0.37)	**0.51** (0.21/0.85)	**−0.35** (−0.58/−0.10)	**0.65** (0.28/1.02)
Summer	**−0.90** (−1.25/−0.54)	**0.70** (0.48/1.00)	*−0.32* (−0.65/−0.04)	**0.78** (0.27/1.36)
Autumn	**−0.77** (−1.07/−0.46)	**0.67** (0.40/0.96)	*−0.36* (−0.61/−0.07)	**0.67** (0.32/1.05)
Southwestern Spain (SWS) Pattern				
Winter	**−0.82** (−1.14/−0.51)	**0.75** (0.47/1.03)	−0.29 (−0.65/0.04)	*0.37* (0.06/0.75)
Spring	**−0.86** (−1.24/−0.50)	**0.75** (0.31/1.21)	**−0.40** (−0.65/−0.11)	**0.85** (0.42/1.33)
Summer	**−0.55** (−0.86/−0.23)	**0.64** (0.24/1.02)	**−0.52** (−0.80/−0.22)	**0.82** (0.24/1.53)
Autumn	**−0.89** (−1.22/−0.54)	**0.37** (0.08/0.68)	−0.18 (−0.44/0.07)	**0.71** (0.39/1.02)

[a]Bold (italic) indicates significance at 1% (5%) confidence level.

[49] Over the course of the twentieth century over Spain, moderately extreme warm nights also indicate significant change over the three spatial patterns that have emerged from the RPCA (Figure 15). These explain 77.6% of the total variance of this index, and they are a slight variant of the SWS pattern including most of southern Spain (Figure 15a) and explaining 29.3% of the total variance; a minor variant of the SEES pattern more centered over the northeasternmost third of Spain (Figure 15b) explaining 26.8% of the total variance; and another variation of the NS pattern (Figure 15c) explaining 21.5% of the total variance. Increases in the number of days per year with daily temperatures higher than the 90th T_{min} percentile are particularly remarkable over southern and northeastern Spain with trends of 0.90 (0.57/1.28) days/decade and 0.77 (0.48/1.07) days/decade, while for northwestern Spain, a more modest positive trend of 0.51 (0.32/0.72) days/decade has been estimated. All trends are statistically significant. On a seasonal basis, spring, summer, and autumn show the most significant increases over southern Spain. Winter contributed a little, with a significant (at the 0.05 level) trend (Table 10). In the case of the SEES pattern, summer, autumn, and spring have similarly high observed rates of change (Table 10), pointing to the important role that the Mediterranean Sea can play during the warm half of the year to forcing increases of moderately extreme warm nights. Over northwestern Spain, winter and autumn reach only moderate significant rates of change, while summer shows the greatest trend, and spring with a lower trend only reached significance at the 0.05 level.

[50] Finally, for moderately extreme cold nights, another three spatial patterns were identified explaining 71% of the total variance: NS (29.8%), SWS (21.8%), and SEES (19.8%) patterns (Figures 16a–16c, respectively). The three patterns show negative rates of change. For the SWS and SEES patterns, the trends are higher [−0.51 (−0.77/−0.24) days/decade and −0.49 (−0.75/−0.23) days/decade] than over NS [0.35 (−0.56/−0.12) days/decade], all significant. These results indicate that over Spain, reductions of cold nights have contributed to a lesser extent to Spanish temperature change over the twentieth century. Summer and spring have been the seasons contributing more to the annual change of cold nights over the SWS pattern, while autumn, spring, and summer have dominated for the SEES pattern. Over the NS pattern, only summer (winter) reached significance at the 0.01 (0.05) level (Table 10).

[51] In summary, the long-term Spanish warming has been accompanied by stronger decreases of cold extremes than increases of warm extremes over the 1850–2005 period, as well as over the course of the twentieth century (not shown). This long-term change in extremes is opposite to that observed at global scales [*Frich et al.*, 2002; *Alexander et al.*, 2006] for the second half of the twentieth century. Furthermore, the most spatially consistent and significant trends also indicate larger and highly significant reductions of cold days and increases of warm days (also shown by the PDF changes in the study of Della-Marta et al., submitted manuscript, 2006) rather than decreases in cold nights and increases in warm nights over the twentieth century. These trends have been identified across all spatial patterns, although annual and seasonal trends of moderately extreme warm nights estimated over the SWS and SEES pattern reached similar rates of change to that estimated for "moderately extreme cold and warm days" for these patterns.

6. Summary and Discussion

[52] An improved and enlarged daily data set of homogenized maximum, minimum, and mean temperatures, with reasonably good spatial coverage, for the period from 1850 to 2005 has been developed and used to document long-term change in the mean and extreme state of Spanish temperature, as well as to assess spatial patterns of Spanish temperature change. A general and highly significant warming on an annual and a seasonal basis has been observed over the entire period and over the course of the twentieth century for the three daily temperature variables. Autumn and winter have recorded the highest rates of change, and spring and summer have recorded the lowest for the T_{mean} regional series. Two periods of rising (1901–

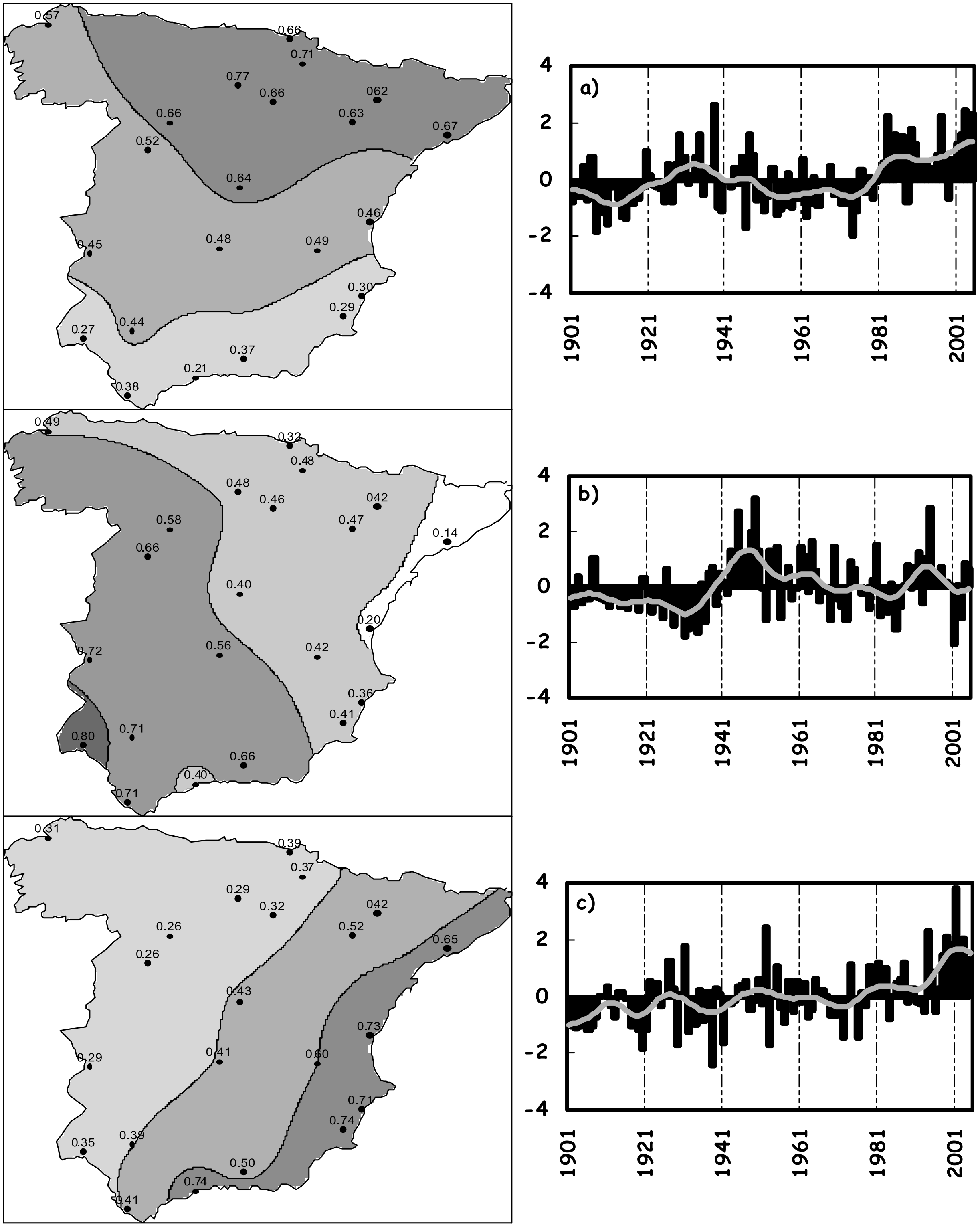

Figure 14. Same as Figure 8 but for annual counts of days exceeding the $T_{\max} > 90$th percentile threshold (in days/decade). (a) NS pattern, (b) SWS pattern, and (c) SEES pattern (see text for details).

1949 and 1973–2005) and one of falling (1950–1972) temperatures were apparent, with the most significant being the unprecedented and strong rise in temperatures observed since 1973 (on an annual basis) associated with greater increases for spring and summer temperatures compared to those for winter and autumn and for the three daily temperature variables.

[53] This increase in daily mean temperatures has been more strongly influenced by greater rates of change in daily maximum than minimum temperatures. Over the twentieth

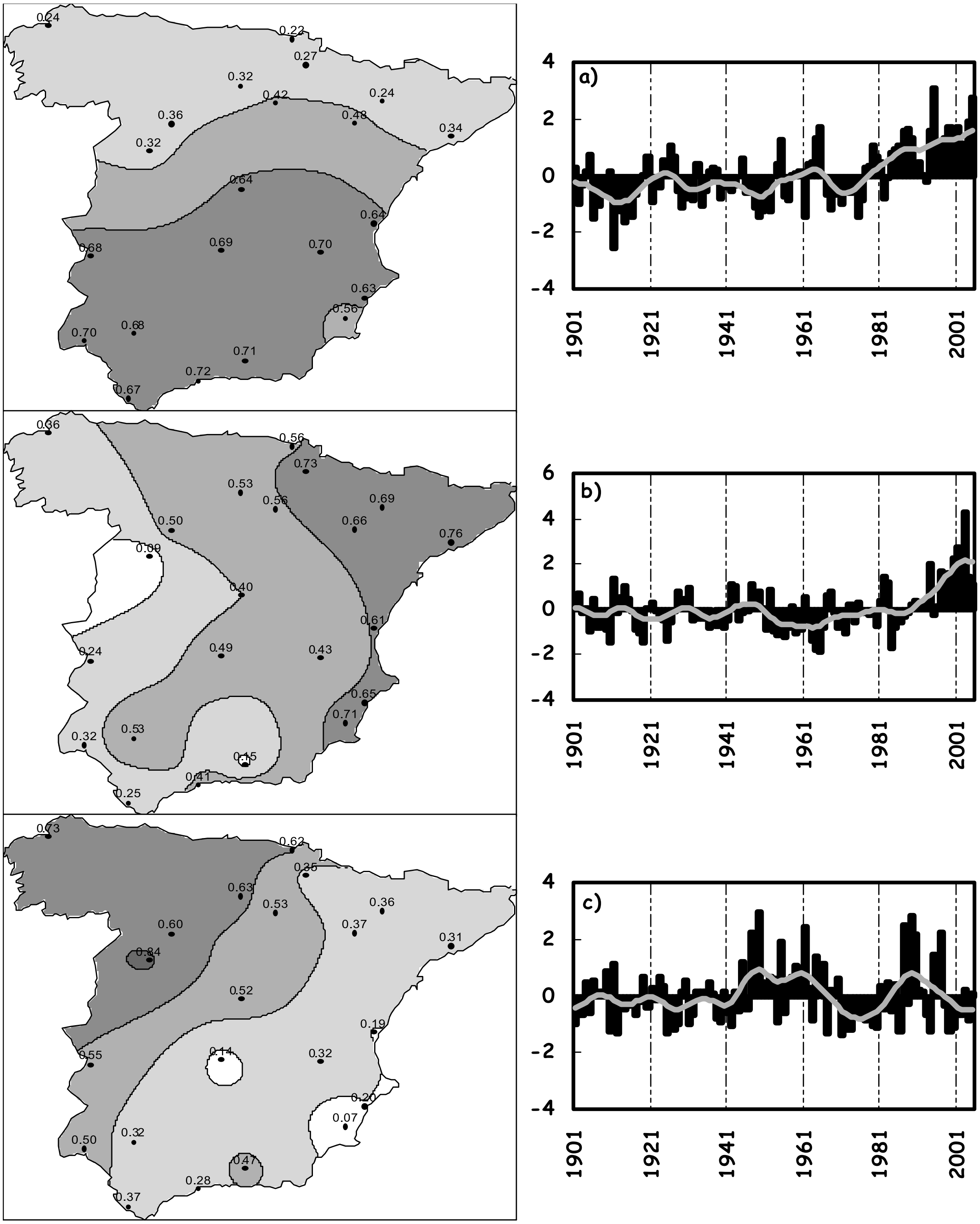

Figure 15. Same as Figure 8 but for annual counts of days exceeding the T_{min} > 90th percentile threshold (in days/decade). (a) SWS pattern, (b) SEES pattern, and (c) NS pattern (see text for details).

century, daily mean temperatures increased at slightly greater rates than for the 1850–2005 period, being associated with a stronger contribution from daily maximum rather than minimum temperatures (about twice as great) on an annual basis. However, different results over the whole of Spain (i.e., higher positive trends for T_{min} than for T_{max} records) have been reported by *Esteban-Parra et al.* [2003a], *Staudt* [2004], and *Staudt et al.* [2005] and over the northern Spanish plateau by *Esteban-Parra et al.* [1995]. These studies also employed monthly homogenized records

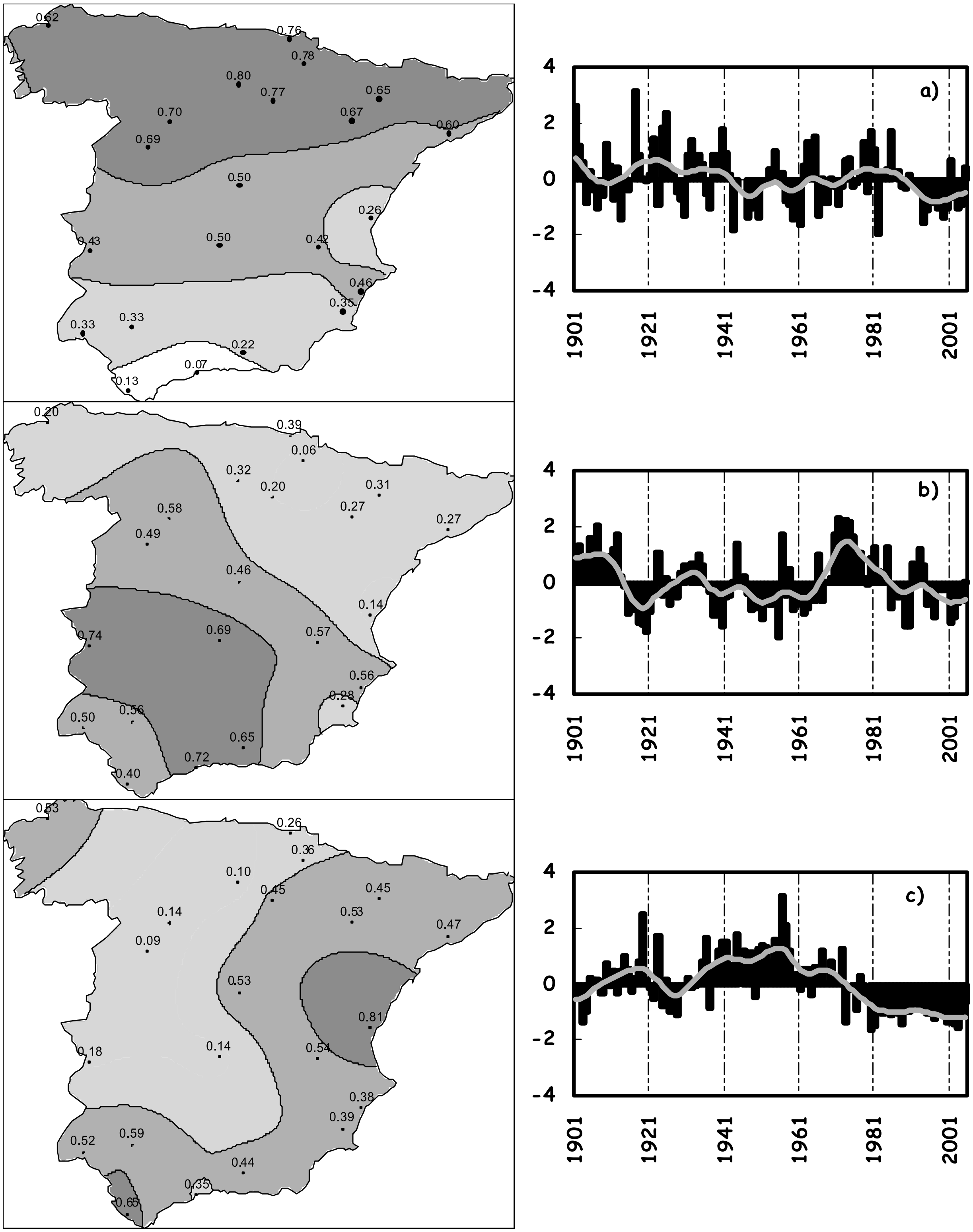

Figure 16. Same as Figure 8 but for annual counts of days exceeding the T_{min} < 10th percentile threshold (in days/decade). (a) NS pattern, (b) SWS pattern, and (c) SEES pattern (see text for details).

going back to the 1870s. As documented in the study by *Esteban-Parra and Castro-Díez* [1996], 56 Spanish monthly T_{max} and T_{min} records were homogeneity checked by means of Thom's and Bartlett's tests, and 41 were adjusted by means of the method of *Jones et al.* [1985]. As an example of the adjustments applied to the data set, the authors showed in their Figure 1 the correction made to the Madrid T_{min} time series. The authors reduced the annual averaged raw data by about 1°C for the earliest period (1869–1892) but did not correct the clear artificial trend that is present in these data from 1893 onward. If these authors proceeded in the same way with other long and urban T_{min} records of their data set, the findings reported in related studies [*Esteban-Parra et al.*, 1995, 2003a] could be biased toward artificially inflated estimates of trends in T_{min} time series. A similar, but more elaborate, relative homogeneity adjustment scheme has recently been developed by *Staudt* [2004]. This study carried out a meticulous testing and adjusting of 43 monthly Spanish T_{max} and T_{min} records, with a specific empirical correction of the urban heat island bias directly applied to 6 out of the 43 T_{min} records, following the *Karl et al.* [1988] approach, and indirectly to the 6 subregional series developed. The application of this empirical approach is based on subtracting from the entire time series the estimated factors according to the time-changing figures in urban populations. Although apparently correct, it tends to negatively overcorrect the data for the entire period for all 6 time series (see Figures 5.9, 5.26, 5.35, 5.44, 5.53, and 5.62 of *Staudt* [2004]). This approach led to unusually lower T_{min} anomalies, particularly for the earliest parts of the records, which could lead to an overestimation of T_{min} series' trends. Therefore the results presented by *Staudt et al.* [2005] indicated an asymmetry between "the rather slight rise of the maximum temperatures (0.4/0.8 °C) and a strong and highly significant increase in the minima (0.8/1.5°C)" estimated since the 1870s.

[54] This is clearly in disagreement with our results (Table 5), which are supported by other groups over different Spanish subregions [*Abaurrea et al.*, 2001; *Brunet et al.*, 2001b, 2001c, 2001d, 2006; *Galan et al.*, 2001; *Horcas et al.*, 2001; *Morales et al.*, 2005]. The fact that these studies are mostly analyzing the post-1920 period or have not made any attempt to minimize the screen bias from the analyzed T_{max} and T_{min} records, as well as that in the present study, daytime temperatures have increased twice as much as nighttime temperatures during 1901–2005 (when screen bias minimization from the T_{max} records has had a small effect on the records), points out the robustness of the current results. Moreover, with independent and neighboring temperature networks to the Iberian Peninsula, different authors have also assessed long-term changes in T_{max} and T_{min} time series (i.e., over Italy by *Brunetti et al.* [2006]), showing excellent agreement with the results reported in this paper with respect to the asymmetrical diurnal warming. However, as stated by *Staudt et al.* [2005], this long-term asymmetry between maximum and minimum temperatures is distinctly broken in the recent decades of accelerated warming, as daytime temperatures have increased as strongly as nighttime temperatures, more in agreement with our results for the 1973–2005 period.

[55] Three spatial patterns of long-term Spanish warming have emerged from an RPCA applied to the adjusted data, which highlight the different roles played by northern (NS pattern), southeastern and eastern (SEES pattern), and southwestern (SWS pattern) parts of Spain to the general Spanish warming over the course of the twentieth century. In this regard, although all three patterns reached high and highly significant trend coefficients, the SWS pattern contributed most to the overall Spanish warming on an annual basis. On a seasonal basis, the SWS pattern again reaches the strongest rates for winter, while spring was more influenced by the SEES pattern; and for summer and autumn, similar rates of change have been estimated over the three patterns.

[56] Finally, stronger decreases in cold extremes rather than increases in warm extremes have accompanied the long-term Spanish warming over the 1850–2005 period. On a seasonal basis, the observed changes in cold extreme temperature indices have been the result of the greater rates of change estimated over winter and autumn, but for moderately extreme warm indices, summer and spring have dominated over winter for increases in warm days. Slightly greater rates of change in the occurrence of extreme temperatures have been associated with the SWS pattern.

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E. Aguilar, M. Brunet, D. López, O. Saladié, and J. Sigró, Climate Change Research Group, University Rovira i Virgili, Pza. Tarraco, 1, 43071, Tarragona, Spain. (manola.brunet@urv.net)

P. M. Della-Marta, Federal Office for Meteorology and Climatology MeteoSwiss, Zurich, Switzerland.

P. D. Jones and D. Lister, Climatic Research Unit, University of East Anglia, Norwich, NR4 7TJ, UK.

A. Moberg, Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91, Stockholm, Sweden.

A. Walther, Earth Sciences Centre, Göteborg University, SE-40530, Göteborg, Sweden.